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RESIDENTIAL SCALE SOLAR DRIVEN COOLING SYSTEMS VERSUS CONVENTIONAL AIR-CONDITIONING IN HOT ARID AREAS: A COMPARATIVE STUDY

Ahmed Hamza H. Ali[1*], Ali Nasser Alzaed[2]

[1]Mechanical Engineering Department, Faculty of Engineering, Assiut University, Assiut 71516, Egypt

[2]Architectural Engineering Department, College of Engineering, Taif University, Al-Haweiah, Taif, Kingdom of Saudi Arabia

*e-mail: ah-hamza@aun.edu.eg

Abstract. In this study, performance, energy efficiency, cost competitiveness, and global warming assessments of residential scale solar thermal and off-grid Photovoltaic driven DC air-conditioning systems versus conventional AC driven air-conditioning system in hot, arid areas is carried out. The first system is an integrated solar thermal driven residential air-conditioning. This system consists of evacuated tube solar collector arrays of area 36 m^2 with high reflective parabolic surface used at the back, a silica gel-water adsorption chiller of 8 kW nominal cooling capacity, and hot and cold-water storage tanks of 1.8 and 1.2 m^3 in volume, respectively. While the second system is an off-grid PV electrically driven DC compressor air-conditioning system. This system is a split air-conditioning unit with a cooling capacity of (26000 BTU) 7.62 kW that requires an input power of 1.8 kW with R410a (1550) refrigerant. Those solar-driven systems are compared with a grid connected AC driven vapor compression Air-Conditioning having 8 kW nominal cooling capacity. Experimental results show that the indoor thermal comfort conditions are achieved in the hottest days of the year for space with a floor area of 80 m^2 with 14 residences for both systems. Comparison between the systems is based on the lifespan of 20 years, cooling capacity 8 kW and 18 hours' daily operation in the cooling session. The results clearly indicate that: Compared with conventional vapor AC driven air-conditioning system, the solar thermal driven cooling system has an energy consumption of 10.94%, with the Total Equivalent Warming Impact (TEWI) of 9.96% while the cost per kW cooling is higher by 295.96%, respectively. While, the off-grid PV driven DC air conditioning system has an energy consumption of 0%, with TEWI of 0.65% and cost per kW cooling is lower by 54.88%, respectively. Therefore, the off-grid PV electrically driven DC compressor air-conditioning system can be recommended for use in the residential sector based on its low cost per kW cooling, no grid energy consumption, and very low environmental impact on global warming. However, this system further cost reduction can be cut from the energy storage, battery subsystem, in case this system is on-grid connected.

1. Introduction

In hot, arid countries, buildings indoor cooling is essential to avoid the thermal stress effects on the occupant. In addition, it is known that worldwide, the increased living standards are accompanied with the buildings occupant demands of thermal comfort. This has been lead to rapid grow in the air-conditioning market in both commercial and residential buildings sectors. Consequently, this followed by increases in energy demand to drive those air-conditioning units. The market available conventional air-condition systems have reached a relatively high standard concerning energy consumption. However, they still require a high amount of electricity that causes significant peak loads on the grids particularly in the countries located in hot, arid climate. The increased energy demands are obvious in most of the Arab countries located in hot, arid climates during summer of 2015. This is based on the number of summer electricity shortages cases created and recorded due to air-conditioning appliances. This rapid growth rate in energy consumption is followed by its negative impact on environmental leads to introducing the renewable energies conversion systems to drive cooling and air-conditioning systems. In the last years, there are many markets available solar energy conversion technologies to drive cooling systems. Solar energy driven cooling systems comprises attractive features as the solar insolation is in a close match with buildings cooling load profile. The solar driven cooling system is comprised of two main sub-systems: solar energy conversion sub-system and energy storage sub-system integrated with the cooling machine. Those sub-systems are classified into two main groups based on the form of energy supply to the cooling machine. They are thermal/work driven system and electricity (Photovoltaic-PV) driven system. Selection of cooling machine type mainly depends on the temperature level of the cold demand as well as the available environment for heat rejection from the system. Until few years ago the focus is on the use of the solar thermal driven cooling and air-conditioning, particularly in domestic buildings. The focus was on the development of the cooling machine integrated with solar thermal driven technologies, to produce cooling, heating, and domestic hot water. Al-Alili et al. [1] provide overviews for working principles of solar thermally operated cooling technologies and reviews for advancements of such technologies. Wiemken et al. [2] cited that the strong development in photovoltaics leads to a competitive advantage of electricity based building supply options. In summer, locally generated PV power may contribute increasingly to the electricity demand of conventional vapor compression air conditioners. In addition, they stated that generating environmental benefits with PV is more cost-efficient than thermal systems (primary energy saving and minimizing the greenhouse gas emissions). This development provokes a competition for solar thermal cooling systems. Mugnier [3] reported that solar air-conditioning is more than ever representing a huge potential of development for solar energy (within 2030 the expected growth of energy demand in buildings especially in developed nations). However, this promising technology is facing one main issue: a general lack of economic competitiveness as it is still the case for many renewable energies conversion technologies unless incentives are in place. Ferreira and Kim [4] presented cooling systems for residential and utility buildings in both South and North Europe and investigates the most promising alternatives when solar energy is to be used to supply the cooling demand of these buildings while the heat rejection temperatures are high. Both the solar electric and solar thermal routes are considered. They concluded that presently vapor compression cycles in combination with PV collectors led to the economically most attractive solutions. Lazzarin [5] evaluated the possible solar cooling systems during a sunny day compared to the PV driven system with respect to the overall system efficiency as well as the investment cost for the various systems. Pons et al. [6] presented the experimental results of six different technologies solar-powered air-conditioners that have been operated in five places from the low-altitude Alps to a tropical island including Mediterranean Sea shore.

Clearly, throughout the literature on residential scale solar is driven cooling systems, there are two main solar cooling technologies. The first is heat-activated systems, which rely on solar thermal energy, while, the second is Photovoltaics (PV) driven conventional vapor system with DC compression. Therefore, this study aim is to compare three residential scale air-conditioning systems in operation in hot, arid areas based on their performance, energy efficiency, cost competitiveness per kW cooling, and their impact on global warming through the systems lifespan. The comparison is done based on the obtained experimental results within applied research project in which two residential scale air-conditioning systems with rated cooling capacity of 8 kW were designed, built, and operated in hot, arid areas in Upper Egypt. The first system was an integrated solar thermal driven residential scale adsorption chiller with a backup gas heater while the second is a conventional electrically driven AC compressor.

2. Systems and methodology

Solar thermal cooling system. The main components of the solar thermal driven adsorption cooling system supply the cooling demand for space with a floor area of 80 m^2 floor area (27.18^{o}N Latitude and 31.19^{o}E Longitude) with 14 residences is shown in Fig.1. The system consists of the following main components: (1) evacuated tube solar collector field with an apparent area of 36 m^2 modified with the back high reflective parabolic surface under the vacuum tubes. The collectors' field is facing south direction, tilted by 22-degree angle with the horizontal, and is arranged in two sub-fields each consist of three parallel arrays and each array consists of a set of three collectors connected in series to provide the required driving heat at specific water temperature. (2) Water hot storage (buffer) tank with an effective volume of 1.8 m^3. (3) Adsorption chiller of 8 kW nominal cooling capacity (two beds silica gel-water) at a driving hot water temperature of 85$°C$ and cooling water temperature of 30$°C$ as reported by the manufacturer. This chiller can operate with hot water supply temperature ranges from 60$°C$ to 95$°C$, and cooling water ranges from 27$°C$ to 32$°C$. (4) Cold water storage tank with an effective volume of 1.2 m^3. (5) 34 kW or 50 kW capacities wet cooling tower for the chiller cooling process and installed on of the rooftop of the building. The 34 KW cooling tower as reported by manufacturer operates at 24$°C$ air Wet Bulb (WB) temperature and 5$°C$ range. Water outlet from the cooling tower is used to extract the heat rejected from the chiller through the intermediate plate and frame heat exchanger connected within the chiller cooling circuit. (6) Cooling load with two 4.5 kW capacity fan-coils. Six-energy saving pumps, an intermediate heat exchanger in chiller cooling subsystem, expansion tanks, backup gas water heater, controllers, measuring sensors and data acquisition system with impeded controller.

Conventional air conditioning system. The measured performance and energy consumption is carried out on split type electrically driven AC compressor conventional air conditioning with 8 kW cooling capacity. The evaporator of the unit is installed in indoor of the conditioned space, and, an air-handling system for cold air outlet from the evaporator that distributed in the conditioned space via a duct having three outlet grilles. The performance of this system is presented by coefficient of performance (COP) as ratio of the cooling capacity of the chiller (from measurement of the air mass flow rate and the average temperature difference across the evaporator) and the electrical input power to the system. Chiller uses R22 refrigerant.

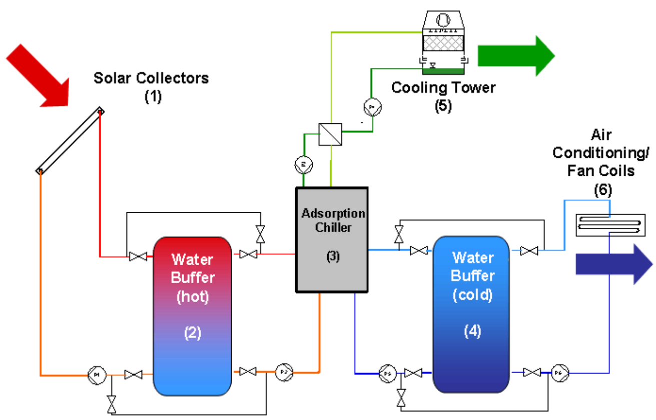


Fig. 1. Process diagram of the solar thermal driven cooling system.

Off-grid PV electrically driven DC compressor air-conditioning system. The schematic diagram of the off-grid PV electrically driven DC compressor air-conditioning system that is used for comparison with the experimentally measured data from the systems in this study is shown in Fig. 2. The system is selected to operate for 18 hrs off-grid, and, it is a DC driven split type air-conditioning unit with a cooling capacity of (26000 BTU) 7.62 kW and require an input power of 1.8 kW with R410a (1550) refrigerant. The following is consider for sizing of this system, the daily solar incident radiation design value is an average of 6 hours around noon in Assiut city (from measurements) is about 800 W/m^2, PV market available monocrystalline silicon type with net energy produced an efficiency of 16.5%. Therefore, the total number of square meters of the required PV panels for 18 hrs operation is about 41 m^2. Two third of the daily generated power should be stored in Batteries i.e. 21.6 kWh storage capacity is required. For batteries available in the market with constant discharge for six hrs with ten years lifespan, durability (assumed to be used) is able to store of 0.24 kWh. Therefore, the total number of required batteries is 90 units.

Measurements, data reduction, and experimental error analysis. The solar thermal driven cooling system was fully automated in operation by the embedded controller in the data logger through a computer interface.

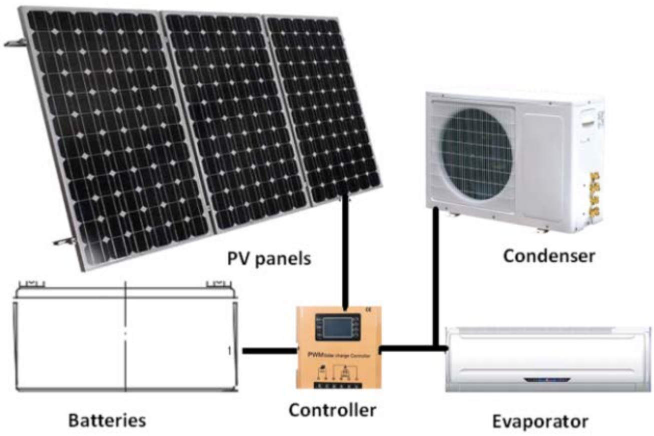


Fig. 2. Schematic diagram of the Off-Grid PV driven DC compressor air-conditioning system.

Also, the data logger with computer interface was used for system monitoring, and data measurements are recording. System operation is done through the following steps: solar collectors' field heats up the water in a closed loop with hot storage tank until the top layers in the storage tank temperature reach to 65°C. At this time, the control system, send an operation signal to start up the chiller and the rest of the pumps in the system except the cooling load pump. The controller sends a signal to stop the solar pump when the top water layer temperature inside the hot storage tank reaches 95°C. In addition, in the case of the outlet water temperature from the collectors' field reach 55°C the solar collectors' field pump is stopped. The chiller continues in operation utilizing the hot thermal energy stored in the hot water storage tank until the inlet temperature to chiller dropped to 65°C. The pumps in all other circuits of the system run in similar control strategies. In the system, all temperatures were measured at a specific location for monitoring, control, and performance analysis. Temperatures were measured by temperature sensors type PT1000. The solar radiation flux is measured at the collectors plan with same tilting angle by Pyranometer with an accuracy of ±0.5% in the measuring range from 0 to 2800 W/m^2, and, 1 % from normalization from 0 to 70-degree zenith angle. Ambient air relative humidity (RH) was measured by a humidity sensor with the standard signal of 0-10 V correspondence to measuring range from 0 to 100% with an accuracy of ± 2 % for the measured values between 30 and 90%. Water flow rate was measured by pulse meters, where six flow meters were used in the system having a measuring range as follows: from 0 to 6 m^3/h for the chiller cooling water and cooling tower circuits. While flow meters with a range from 0 to 2.5 m^3/h are used in the solar collectors' field circuit, the chiller is driving hot water circuit, chiller chilled water circuit and cooling load fan coils circuit. For system control purpose, the gauge pressure at several points in the system circuits was measured by pressure transducers having a measuring range from 0 to 6 bars.

Assessment of solar thermal driven cooling system performance in operation under hot, arid climate requires determination of the chiller driving thermal power, the chiller chilling capacity, and collectors' filed useful gained thermal power. The quantities of those parameters are determined from the measured data as follows:

$$Q = m \times \dot{C_p} \times \Delta T, \quad (1)$$

where:

Q= heat rate (kW)

$\dot{m}$= water mass flow rate (kg/s)

C_p= water specific heat (kJ/kg. °C)

ΔT= temperature difference (°C)

The chiller coefficient of performance is determined by:

$$COP = \frac{Q_{chw}}{Q_{input}}, \quad (2)$$

where:

COP= chiller coefficient of performance

Q_{chw}= chiller chilling capacity (kW)

Q_{input}= chiller driving power (kW)

The collectors' field overall efficiency is determined by:

$$\eta = \frac{Q_{cll}}{G_T \times A_{cf}}, \quad (3)$$

where:

η = collector field overall efficiency

Q_{cll}= collectors' filed output thermal power (kW)

G_T= total measured incident solar radiation flux on the collectors field surface (kW/m^2)

A_{cf}= apparent total area of the solar collectors' field (m^2)

In this study, the uncertainty in the determined quantities based on the measured values and the instrumentation accuracy were calculated using the formulas of Coleman and Steele [7]. The uncertainty reported by the manufacturers' sheets of the instrumentation used to measure temperature, solar radiation; water mass flow rates were used in experimental error analysis. Throughout all experiments, it is found that the average uncertainties are as follows: in the temperature was 0.29%, heat transfer rates were 4.2%, *COP* was 4.8%, and collectors' efficiency was 2.6%.

Global warming assessment. The global warming assessment in this study is evaluated with neglecting the embedded energy in the three investigated systems components; it is based only on their operation impact on the global warming gas emissions. The main measure for the global warming assessment is estimating the Total Equivalent Warming Impact (TEWI), which applies to measures the efficiency of a refrigerant by combining its direct and indirect global warming contribution expressed in kg of CO_2 equivalent. In this study, the TEWI are estimated for the lifespan of the three systems is 20 years for with equal cooling capacities of about 8 kW. The indirect contribution is based on the energy consumption of the system components with CO2 equivalents produced by power stations. Each country has a tabulated value of conversion of the energy consumed from kWh into equivalent kg CO2. Also, all greenhouse gas (GHG) emissions can be converted into CO2 equivalents. Each greenhouse gas (GHG) has a different global warming potential (GWP) and persists for a different length of time in the atmosphere. The three main greenhouse gasses and their 100-year global warming potential (GWP) compared to carbon dioxide are (1) carbon dioxide (CO2) - 1 x, methane (CH4) - 25 x and the strongest GWP is the nitrous oxide (N2O) - 298 x. The TEWI factor expressed in kg of CO2 determined by:

TEWI = Leakage rate + Recuperation rate + Indirect emissions due to energy consumption, (4)

where

*Leakage rate = Mass of refrigerant leaking from system * GWP of Refrigerant* (5)

The recuperation rate is obtained as follow:

*Recuperation rate = GWP * Charge *(1- Recuperation factor)* (6)

The Recuperation factor is the percentage of refrigerant recovered when a refrigeration or air conditioning equipment reaches the end of its useful life. Indirect Emissions are emissions of CO2 occurred by electricity generation of required to drive the refrigeration or air conditioning equipment during its lifetime. It estimated as follow:

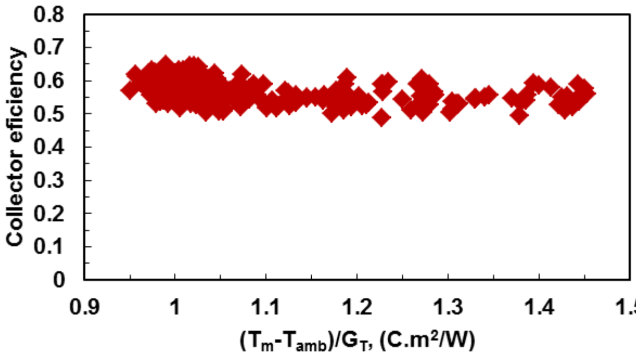
*CO2= Machine life * Energy consumption* Emission factor,* (7)

where the emission factor is the amount of CO2 released into the atmosphere when fuel burned to produce one kWh of electricity.

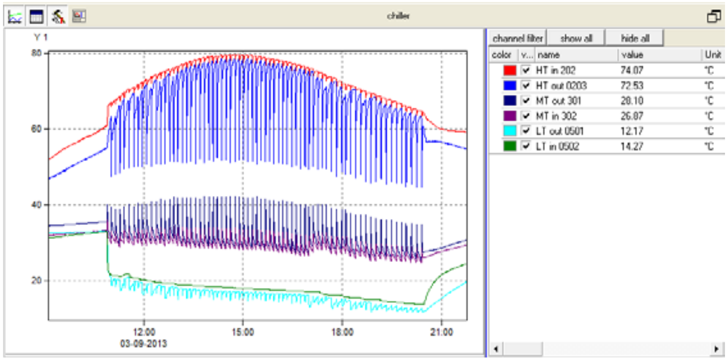
The emission factor for electricity varies from country to country and according to the primary source of energy, in Egypt, the factor is 0.55 kg CO2/kWh. The typical leakage rates used in this study for Hermetic compressor are 1-2% and for split units are 6-8% per year annum (pa). For the vapor compression systems, the following data are used. Average leakage rate pa: 1.5%, Lifespan of equipment: 20 years, GWP of R22 refrigerant is equivalent to1500 kg CO2, GWP of R410a (1550) refrigerant is equivalent to1720 kg CO2 and Recuperation factor assumed to be 50%.

3. Results and discussion

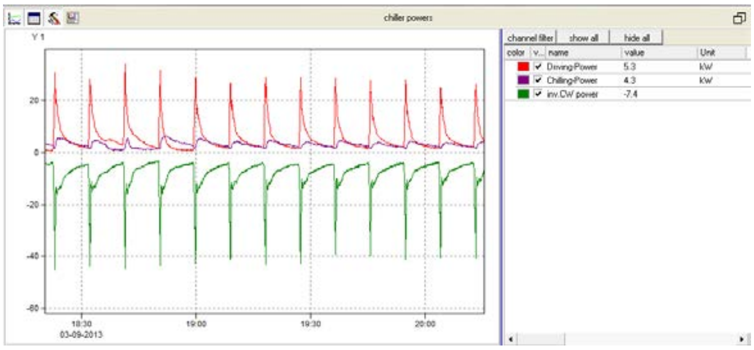
System performance. The solar thermal driven adsorption cooling system is in operation since summer 2012 until now. Therefore, a large amount of measured data and results were obtained. However, only sample of performance assessment results for a day during those years are presented and discussed. The performance of the system is expressed in terms of the solar collector field efficiency, cooling tower outlet temperature, chiller chilling capacity, the temperature of chilled water outlet the chiller and the chiller coefficient of performance (*COP*). Fig. 3-a shows the instantaneous solar collectors' field efficiency as a function of the mean average temperature of the water inside the collectors the collectors' filed (Tm), the ambient air dry bulb temperature, and the incident solar radiation on the collector plane according to ASHARE 93-77 Duffie and Beckman [8]. The presented data are corresponding to the measured values obtained for 2 hours before and after the noon. Clearly from Fig. 3-a, the collectors field efficiency is ranged from 46.7 % to 66.4 % as the inlet water temperature ranged between 56.7$°C$ and 73$°C$, and the outlet water temperature ranged from 67.7$°C$ to 83.5$°C$, ambient air temperature ranged from 30$°C$ to 36$°C$, the solar radiation flux was between 795 and 991 W/m^2, respectively. The figure clearly shows that the collectors' field efficiency was almost constant during the day. This is expected for vacuum tube collectors with a parabolic high reflective surface under the evacuated tubes in collectors. The daily solar collector efficiency during the reported period of system operation ranged from about 50 % to 78 %. Assessment of the sub-system components performance is carried out for a moderate weather day of September 3, 2103, and is presented in Fig. 3-b and 3-c. The figure shows the operational characteristics of the adsorption chiller that obtained as a screen shot from the data logger software. Fig. 3-b shows screen shot for the driving hot water temperature inlet and outlet from the chiller (HT), chiller cooling water temperature inlet and outlet from the chiller (MT) and cold-water temperature outlet and inlet to the chiller. While, Fig. 3-c shows screenshot for the chiller driving thermal power, chilling power and heat rejected power (CW power).



(a)



(b)



(c)

Fig. 3. Sub-system components performance is for September 3, 2103 (a) solar collectors' field efficiency, (b) screen shot from the data logger for driving hot water temperature inlet and outlet from the chiller (HT), chiller cooling water temperature inlet and outlet from the chiller (MT) and chilled water temperature outlet and inlet to the chiller and (c) screen shot from the data logger for the chiller driving thermal power, chilling power and heat rejected power (CW power).

Clearly, the results shown in Figs. 3-b and 3-c indicate that the chilled water outlet temperature from the chiller is 20.6°C and decreases with time until reach to 12.2°C, while the chiller is cooling water temperature decreased from 31.4˚C at the start and became 26.9°C at the end of this day experiment. The chiller driving hot water temperature was 65°C at the beginning of the experiment and reaches to 80.4°C around noon, and, then decreased again. For that day, the total driving heat energy supplied to the chiller was about 310 MJ; the solar energy obtained from the collectors' field was about 439.5 MJ. In that day the collector field, average efficiency was 0.5 and the chiller produced about 136.1 MJ cold energy with daily chiller COP of 0.44. For the chiller working hours, the average chilling power was about 3.6 kW, which presents about 45% of the rated chiller nominal capacity. These results mainly attributed to the higher inlet cooling water temperature to the chiller to cool both the adsorber and condenser. The overall results of the cooling session for summer of 2012 are summarized as follows. The chiller average daily COP was 0.41 with the average chilling power of 4.4 kW at the cooling water outlet temperature from the cooling tower of $31°C$, and the outlet chilled water temperature was about $19°C$, correspondence to average outdoor Ambient Dry Bulb temperature of about $40°C$ and Wet Bulb temperature of about of $21°C$. Therefore, based on cooling tower outlet water temperature of $31°C$ the city water at a temperature of $27.5°C$ was used as the chiller cooling medium instead of the water outlet from the cooling tower, and, this process leads to enhancement the chiller COP by 40 % and the chilling capacity of the chiller by 17 %.

The performance of the conventional AC driven chiller, energy consumption, and cooling capacity for three consequent operation days are shown in Fig.4. Cleary, from the experimental results presented in Figs. 3 and 4 both systems show that the indoor thermal comfort conditions are achieved in the hottest days of the year for an area of 80 m2 with 14 residences. However, the electricity consumption and consequentially the CO2 equivalent emission are different for both systems. The performance parameters of PV driven DC compressor air-conditioning system cannot be reported, as this system is not yet installed on the site under investigation.

Energy efficiency, cost competitiveness, and global warming assessments. The estimated lifespan of the energy consumption, cost per kW cooling (using the formula and procedure presented in Vartiainen et al. [9] and the impact on the global warming assessments of the three residential scale systems operation in hot, arid areas are presented in table (1). Compared with conventional AC driven air-conditioning unit having the same cooling capacity and an equal number of working hours during the three systems lifespan, the results clearly indicate that solar thermal driven cooling system has an energy consumption of 10.94%, with TEWI of 9.96% and cost per kW cooling of 295.96%. While, the off-grid PV Driven DC Air Conditioning System has an energy consumption of 0%, with TEWI of 0.648% and cost per kW cooling of 54.88%. Therefore, the off-grid PV Driven DC Air Conditioning system is highly recommended for use in residential sector application based on its low cost, zero grid energy consumption, and very low impact on global warming. Further cost reduction can be cut from the energy storage subsystem if the system is on-grid connected.

4. Conclusions

In this study, performance, energy efficiency, cost competitiveness, and global warming assessments of residential scale solar thermal and off-grid Photovoltaic driven DC air-conditioning systems versus conventional AC driven air-conditioning system in hot arid areas is carried out. The first system is an integrated solar thermal driven residential air-conditioning. This system consists of evacuated tube solar collector arrays of area 36 m^2 with high reflective parabolic surface used at the back, a silica gel-water adsorption chiller of 8 kW nominal cooling capacity, and hot and cold water storage tanks of 1.8 and 1.2 m^3 in volume, respectively. While the second system is an off-grid PV electrically driven DC compressor air-conditioning system. This system is a split air-conditioning unit with cooling capacity of (26000 BTU) 7.62 kW that requires an in put the power of 1.8 kW with R410a (1550) refrigerant.

Table 1. Estimated Lifespan Energy Consumption, Cost per kW Cooling and Global Warming Assessments of the Three Residential Scale Cooling Systems.

System type	Energy Consumption in MWh	TEWI, equivalent Tons CO2	Cost per kW cooling in US$
Conventional Air Conditioning System	757.7	416.7	2.970
Solar Thermal Cooling System	79.5	45.6	8.790
Off Grid, PV Driven DC Air Conditioning System	-	2.7	1.630

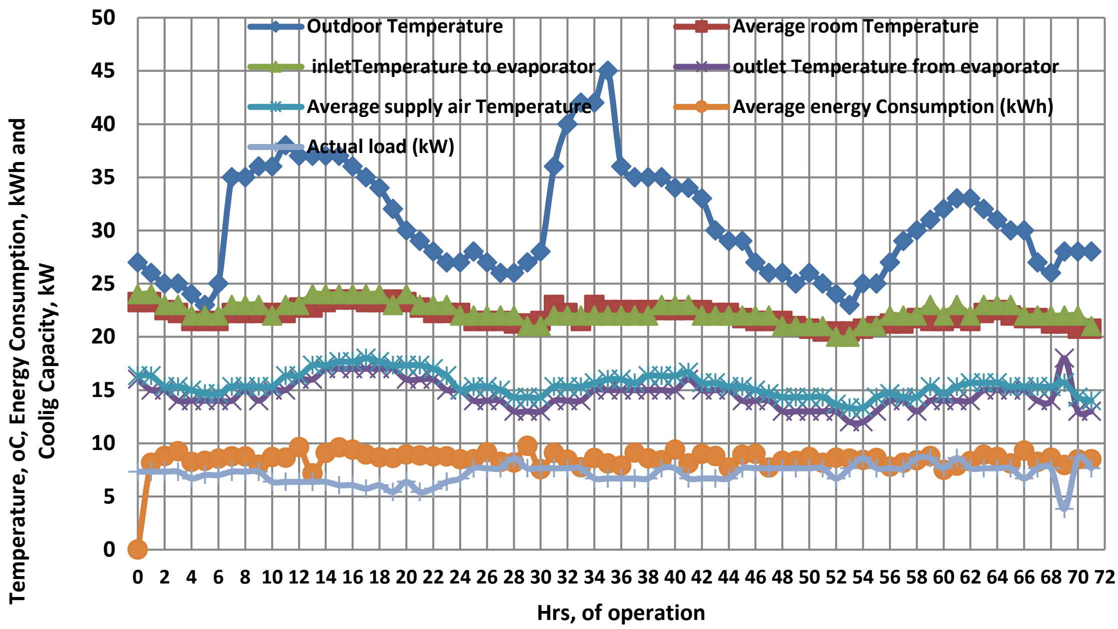


Fig. 4. Performance, energy consumption, and cooling capacity of the conventional AC driven chiller for three consequent operation days.

Those solar driven systems are compared with a grid connected AC driven vapour compression Air-Conditioning having 8 kW nominal cooling capacity. The following can be concluded from the obtained results:

Experimental results show that the indoor thermal comfort conditions are achieved in the hottest days of the year for space with a floor area of 80 m^2 with 14 residences for both systems.

The results clearly indicate that: compared with conventional vapour AC driven air-conditioning system, the solar thermal driven cooling system has an energy consumption of 10.94%, with TEWI of 9.96% and cost per kW cooling higher by 295.96%. While, the off-grid PV driven DC air conditioning system has an energy consumption of 0%, with TEWI of 0.648% and cost per kW cooling less by 54.88%.

The off-grid PV driven DC compressor air-conditioning system can be recommended for use in the residential sector based on its low cost per kW cooling, no grid energy consumption, and very low environmental impact on global warming. However, this system further cost reduction can be cut from the energy storage, battery subsystem, in case this system is on-grid connected.

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