Energy Consumption and Operating Cost of a Solar/Gas Powered Absorption Air Conditioning System

Talib Ahmadu*, Fatai Anafi and Danjuma Yawas

Department of Mechanical Engineering, Faculty of Engineering
Ahmadu Bello University
Zaria, Nigeria

ABSTRACT

Electrically powered vapor compression systems are usually employed in air conditioning of buildings. However, there are concerns over the high power consumption by these systems which lead to high electricity bills. Absorption cooling has the prospect to consume lower power. This study has carried out an assessment of the energy consumption and operating cost of a solar and gas powered absorption air conditioning system. The experimental plant has a prototype absorption chiller which operates on the lithium bromide/ water pair. The thermal energy requirement is supplied by solar energy via solar collector as well as an auxiliary gas burner powered by liquefied petroleum gas. The experimental plant was run under varying weather conditions in both solar and gas heating modes to cool a test room. Energy consumed as well as the cost of energy consumed were computed. Results showed the least gas consumption occurred on days with high solar fraction. Total daily energy consumption cost varied from $0.6/day for a day with solar fraction of 0.6 to $ 1.21/day for a day with solar fraction of 0. The cost of electric power consumption of the absorption system was lower in comparison to that of a conventional vapor compression chillers in the order of 44.4% to 64.2%. However, the cost per kWh of cooling for the conventional vapor compression chiller was lower than that of the absorption system.

Keywords: *Energy, absorption, air conditioning, solar, cost*

1.0 INTRODUCTION

There has been a growing increase in the energy demand for refrigeration and air conditioning over the years especially in developing countries. This is as a result of the continued need to prevent food spoilage as well as satisfy indoor comfort demands [1]. Usually, electrically powered vapor compression systems are mostly used in air conditioning of buildings. However, these vapor compression systems consume high electric power, which leads to high electricity bills [2]. Also, these units operate with synthetic refrigerants such as hydro–chlorofluorocarbons (HCFCs), which when released into the atmosphere constitute high Ozone Depleting Potential (ODP) [3]. Thermally driven absorption air conditioning systems have the ability of working with low grade energy such as waste heat or solar energy. They consume low electric power as well as have the ability to work with refrigerants with no harmful effect on the environment, such as water [4].

*Corresponding email: talibahmadu@gmail.com

The need to safe guard the environment from harmful refrigerant emissions as well as minimize cost associated with power consumption have led to renewed research interest in thermally driven absorption air conditioning systems. In this regard, several researchers have carried out works on thermally driven absorption air conditioning in different climates.

The performance, economic and environmental benefits of a 10 kW NH_3/H_20 solar absorption air conditioning system under Abu Dhabi's weather conditions has been studied. The system was found to consume 47% less electrical energy than a vapor compression system of the same cooling capacity [5]. An experimental work on a solar and gas fired absorption system for cooling and heating in China was done. The gas consumption of the hybrid energy system had a 49.7% energy savings ratio compared with conventional gas fired system [6]. An experimental study on a mini type solar absorption air conditioning system of 8 kW capacity in China has been carried out. The system was found to consume 27% less power than a conventional chiller of same capacity [7]. Albers carried out an experimental work on solar absorption cooling system in Germany. Results showed that seasonal energy efficiency ratio of above 0.75 was attained [8]. A solar powered absorption air conditioning system has been operated under Thailand weather conditions. It was found that solar collector delivered a yearly average 81% of the thermal energy required by the chiller with the remaining 19% generated by liquefied petroleum gas (LPG) fired back up heating unit [9]. TRNSYS simulation of a solar absorption air conditioning system under China weather conditions showed 66% reduction in primary energy consumption [10]. Optimization of a solar absorption air conditioning system for an Australian home showed the system consumes 50% less electric power than that of a conventional system [11]. A simulation study of an absorption air conditioning system under the climate conditions in Morocco showed an average solar fraction of 0.3 [12].

This work is aimed at evaluating the energy consumption as well as the daily operating cost for an experimental scale solar and gas powered absorption air conditioning system of 3 kW cooling capacity, operating under the weather conditions of Zaria in Nigeria.

1.1 Principle of Operation of the Absorption Air Conditioning System

Figure 1 shows a schematic of the solar/gas absorption air conditioning system. Hot water is generated at the solar collector via solar radiation from the sun. The hot water is stored in a hot water tank. An auxiliary gas burner powered by liquefied petroleum gas is attached to the hot water tank to provide the required thermal energy in cases of low or no solar radiation. From the hot water tank, the hot water is pumped to the absorption chiller, which consists of a generator (G), condenser (C), absorber (A), evaporator (E) and a solution heat exchanger (SHX). Desorption of the refrigerant (water) takes place at the generator, while condensation of the refrigerant vapor takes place at the condenser. At the absorber, solution of lithium bromide absorbs water vapor from the evaporator. The resulting chilled water is produced at the evaporator, which is then pumped to the building through fan coils to provide the desired cooling. An external cooling tower is used to take away the heat generated at the condenser and absorber. P1, P2, P3, P4 and P5 are pumps that facilitate the fluid flow, while V1 and V2 are the flow valves.

The absorption cooling system is heat driven, since it requires heat to desorb the refrigerant from the solution of refrigerant and absorbent. This heat is usually low temperature heat (between 70–100^{o}C) for the most commonly used single effect type [4]. This heat can easily be attained from solar energy using solar collectors, gas burners or waste heat from industrial processes. The absorption cooling system also requires a fraction of electricity to power the pumps and fan. It is therefore expected to consume less power than a conventional cooling system of the same capacity.

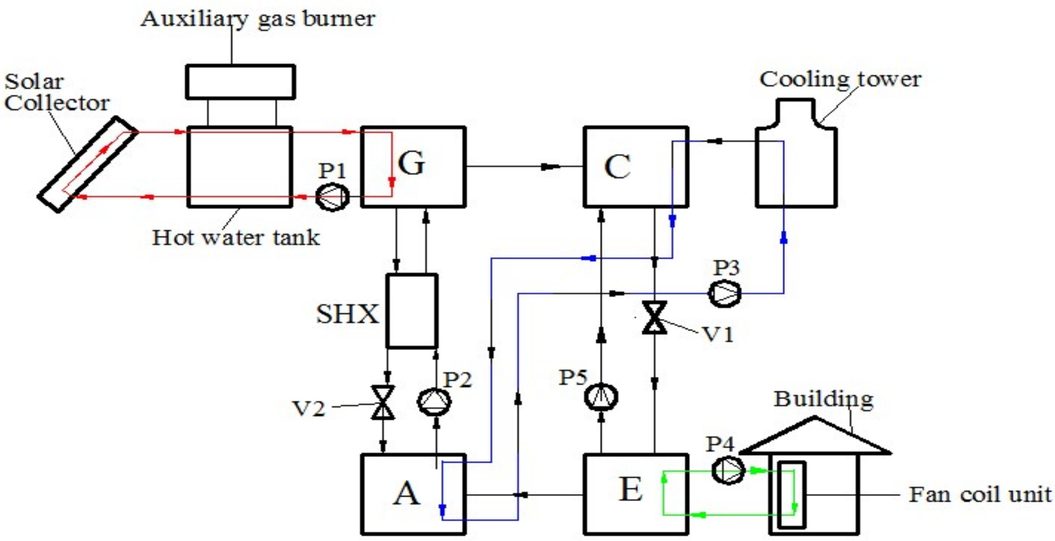

Figure 1: Schematic of the solar/gas absorption air-conditioning system

2.0 METHODOLOGY

Experiments were conducted on an experimental scale solar and gas powered absorption air conditioning system, developed at the department of mechanical engineering, Ahmadu Bello University, Zaria. The entire system consists of: an absorption chiller of 3 kW cooling capacity, which works on the lithium bromide water pair. A solar collector, which uses solar radiation to generate the thermal energy required for the hot water. A gas burner powered by liquefied petroleum gas, which provides thermal energy required in cases of low solar radiation. A storage tank, which stores the hot water. A wet cooling tower, to which waste heat is rejected and an indoor fan coil unit which distributes cooled air to the test room. This paper presents findings from the evaluation of the energy consumption as well as operating cost assessment of the experimental plant.

2.1 Experimental Procedure

The experiments were conducted on selected days in the months of April and June 2017, under steady state conditions. Each day spanned from 9.00 am to 5.30 pm. Two heating modes were employed to provide the thermal energy required for the hot water: the solar power heating mode, provided via the solar collector and the gas burner heating mode, provided by liquefied petroleum gas burner. The gas burner heating mode was used in periods when the solar radiation was not sufficient to generate the required thermal energy. Chilled water was produced at the evaporator in the absorption chiller and pumped to the fan coil unit where cooling of the test room was achieved.

Measurements were made every fifteen minutes from the various measuring instruments attached to specific points on the system. Figure 2 is a schematic of the experimental set up. T1 to T7 are the digital thermometers attached to the positions on the system. They were used to measure temperature at the locations. The temperatures measured include the collector fluid temperature, hot water, chilled water and cooling water temperatures. The room temperature was also measured. F1 to F4 are the flow meters and were attached to the locations to measure the flow rates. The flow rates measured include the hot water, chilled water and cooling water flow rates. PG1 and PG2 are the pressure gages and were used to measure the pressure within the chiller. The solar power was measured using a solar meter. The gas consumed was measured by placing the gas burner on a digital weighing scale and taking measurements as a result of the weight loss at intervals. A watt meter was used to measure the electric power consumption of the chiller. The total power consumption by the system from the pumps and fan was 0.5 kW. Figures 3 and 4 show components of the experimental absorption air conditioning system and section of the absorption chiller, respectively. Table 1 shows the measuring instruments used and their specifications.

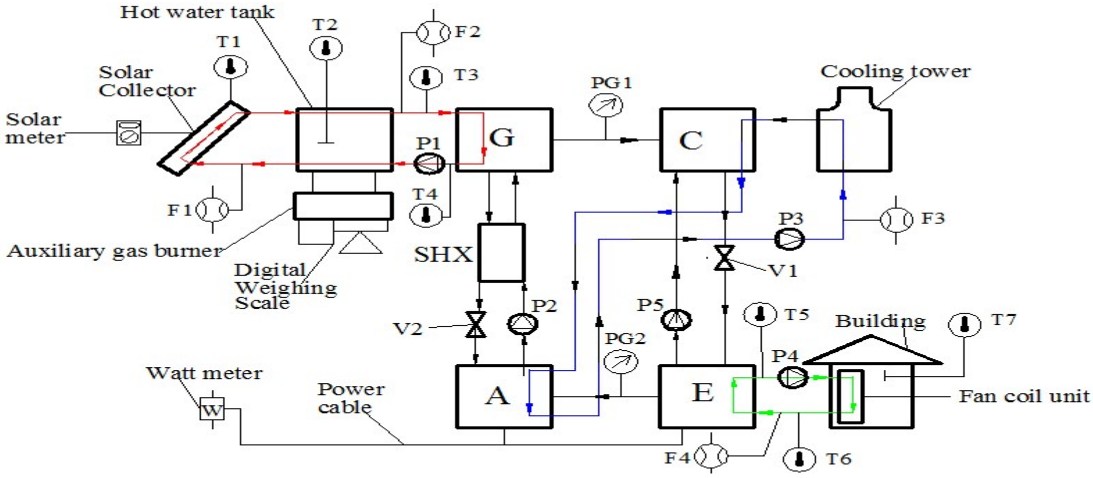

Figure 2: Schematic of the experimental set up

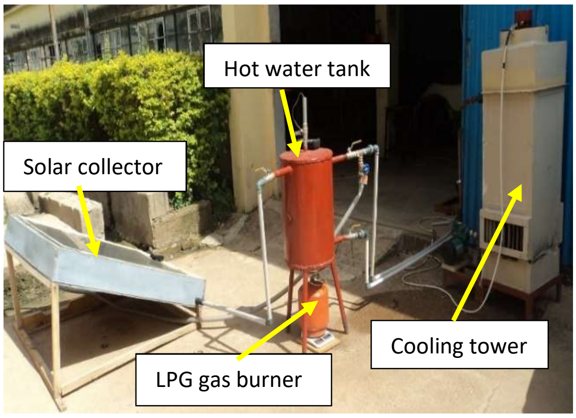

Figure 3: Outdoor components: solar collector, hot water tank, gas burner, cooling tower

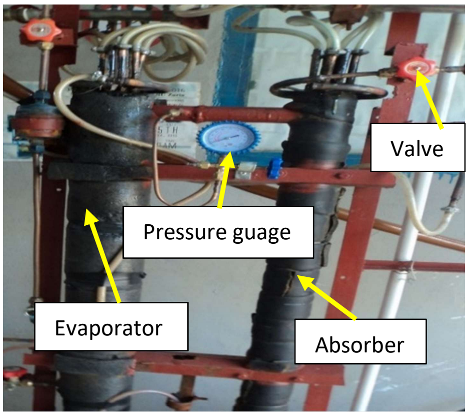

Figure 4: Section of the absorption chiller

Table 1: Measuring instruments

S/No.	Instrument	Model No.	Measuring Range	Accuracy
1	Digital thermocouple thermometer	T407291	50-1300 °C	0.1%+1°C
2	Digital solar power meter	DBTU 1300	0-2000 W/m^2	±5% of reading
3	Digital flow meter	PT-11	0.1-100 L/h	±4% of reading
4	Digital weighing scale	SF-400	0-7000 g	±1 g
5	Pressure gage	ASME B40-100	1-24 bar	±2% of reading
6	Watt meter	H3680W	0-3680 W	Class 1.0

2.2 Evaluation of Parameters

The parameters were evaluated as described in the following subsections.

2.2.1 Solar fraction

The solar fraction was calculated as a ratio of the number of hours of the day in which the system was powered in the solar heating mode to the total hours of operation of the day.

2.2.2 Gas consumption

The weight of gas consumed at an interval of time was determined by weight difference over the time interval using a digital weighing scale. The gas consumption in kW(P_{gas}) was computed using:

$$P_{\text{gas}} = \frac{mC\quad_{\text{g}}}{t} \tag{1}$$

where

m: the weight of the gas consumed in the time interval (kg)
Cal_{g}: the calorific value of liquefied petroleum gas taken as 46.1MJ/kg [13]
t: the time interval in which the gas was used

2.2.3 Cooling power (Q_{e})

The cooling power was calculated according to [14] as follows:

$$Q_{\text{e}} = \dot{m}_{\text{e}} C_{\text{p}} (T_{\text{e2}} - T_{\text{e1}}) \tag{2}$$

where

$\dot{m}_{\text{e}}$: the mass flow rate of chilled water at the evaporator $= 0.31Kg/s$
C_{p}: the specific heat capacity of the chilled water
T_{e2} and T_{e1}: the outlet and inlet chilled water temperatures to the evaporator, respectively

The daily cooling produced in kWh was computed as:

$$Daily\ cooling\ produced\ (kWh) = Q_{\text{e}} \times h \tag{3}$$

where h is the daily hours of operation.

2.2.4 Power consumption of conventional chiller

The Energy Efficiency Ratio (EER) is the ratio of cooling output from a conventional chiller to the power consumed by the chiller. Average allowable EER specifications for conventional vapor compression chillers manufactured in different countries according to [15] was used. Consequently, the power consumption for conventional vapor compression chillers resulting from the different EERs were computed for a 3 kW cooling capacity chiller using Equation (4) as follows:

$$Power\ consumed\ by\ conventional\ chiller = \frac{Cooling\ output}{EER} \tag{4}$$

2.2.5 Cost per kWh cooling

The cost per kWh of cooling was calculated according to Equation (5) as follows:

$$Cost\ per\ kWh\ cooling = \frac{Cost(Dollars)}{Cooling\ produced\ (kWh)} \tag{5}$$

where the cooling cost for the absorption cooling system was calculated using Equation (6) expressed as:

$$Cooling\ cost(Dollars) = (Electricity\ consumed(kW) \times Time(hrs) \times Electricity\ tariff) + (cost\ of\ gas\ consumed) \tag{6}$$

For the study location, the electricity tariff was \$ 0.075/kWh, while the cost of LPG gas was \$ 0.95/kg.

3.0 RESULTS AND DISCUSSION

The days were classified as: Hot clear sky day: days with very clear sky, hot weather with high solar radiation. Fairly clear sky day: days with intermittently clear sky and partly cloudy sky, average solar radiation. Cloudy sky day: days with very cloudy sky, low solar radiation.

Accordingly, the days were classified as follows:

Hot clear sky: April 22, June 6, 2017
Faily clear sky: June 3, June 8, 2017
Cloudy sky: June 12, 2017

Figure 5 shows the variation of solar fraction for the experimental days. April 22 and June 6 are seen to have recorded the highest solar fractions of 0.6 and 0.52, respectively. This was due to the clear sky and high solar radiation recorded on these days. The days of June 3 and June 8 recorded lower solar fractions. This was due to fairly cloudy nature of these days. There was zero solar fraction for the day of June 12. This was because the day was very cloudy with very low solar radiation, thus the system was powered in the gas burner heating mode throughout the day.

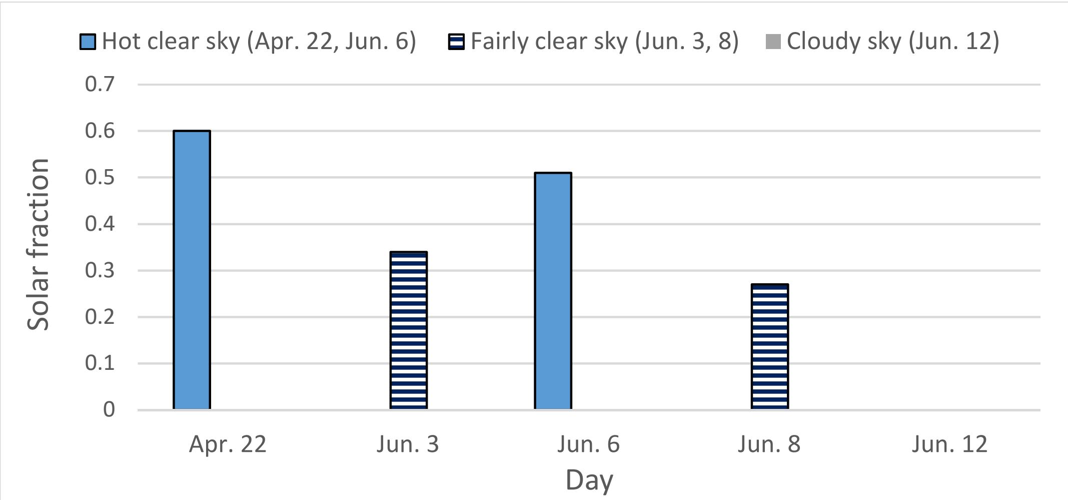

Figure 5: Variation of solar fraction for the experimental days

Figure 6 shows the variation of daily cooling produced for the experimental days. A total of 13.3 kWh of cooling was produced on April 22. This was because of the high solar radiation recorded over a long interval of time. Thereby reducing the frequency of switching from solar to gas heating modes. This is followed closely by 13.1 kWh of cooling recorded on June 12. This relatively high cooling output was because the system was powered on the gas burner heating mode throughout this day, as solar radiation was not available. There was no switching between the heating modes and therefore the system was stable. The least cooling output of 11.7 kWh and 11.1 kWh were recorded on June 3 and 8, respectively. This was because the days were intermittently sunny and cloudy, thus there were several instances of switching between the heating modes. This makes the system less stable.

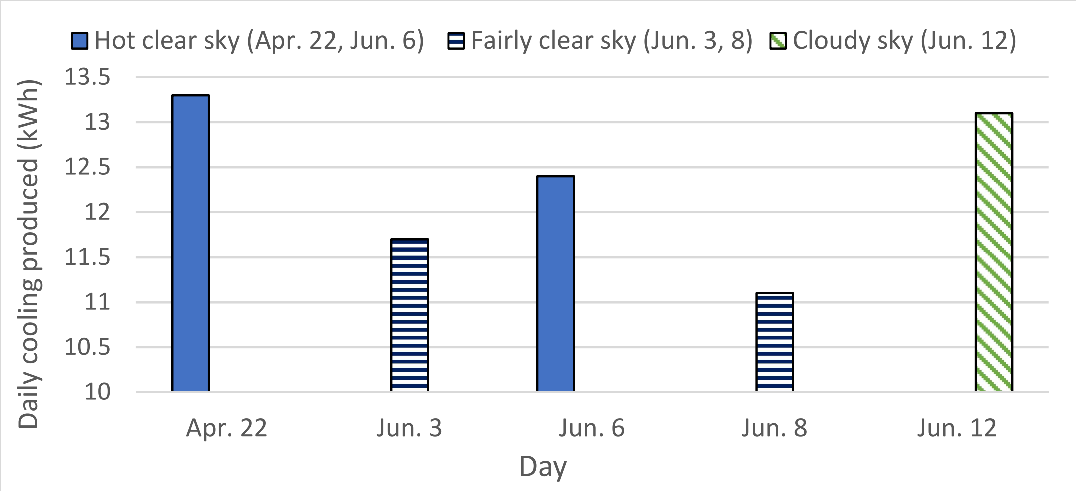

Figure 6: Variation of daily cooling produced for the experimental days

Figure 7 shows the daily variation of electricity consumption and gas consumption for the experimental days. It can be observed that the electricity consumption is constant at 4 kWh for all the experimental days, as the system consumes 0.5 kW and runs for 8 hours daily. The gas consumption is seen to be lowest at 4.09 kWh and 5.24 kWh on April 22 and June 6, respectively, which recorded high solar fractions. Gas consumption is highest on June 12 at 12.28 kWh having recorded zero solar fraction. The higher the solar fraction, the less gas consumed and vice versa.

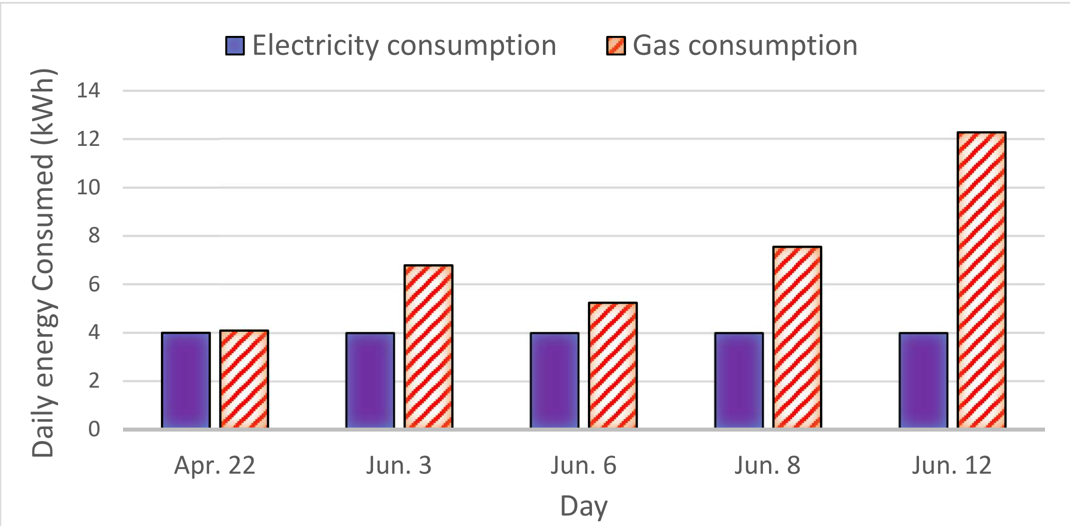

Figure 7: Variation of energy consumed for the experimental days

Figure 8 shows the daily cost of electricity consumed by the absorption air conditioning system in comparison to the daily cost of electricity consumed by conventional vapor compression chillers of same capacity with varying energy efficiency ratio. It can be observed that the absorption air conditioning system has the least cost of electricity consumption at \$ 0.038, having consumed the least electric power. The cost is highest for the chiller with the lowest energy efficiency ratio of 2.14 at \$ 0.1. The reduction in cost of electricity consumption by the absorption system over the conventional chiller is within 44.4% to 64.29%, depending on the energy efficiency ratio of the conventional chiller. This result is similar to the findings of [5], who reported a reduction of 47% in electricity consumption by an absorption air conditioning system over conventional cooling system under Abu Dhabi weather conditions.

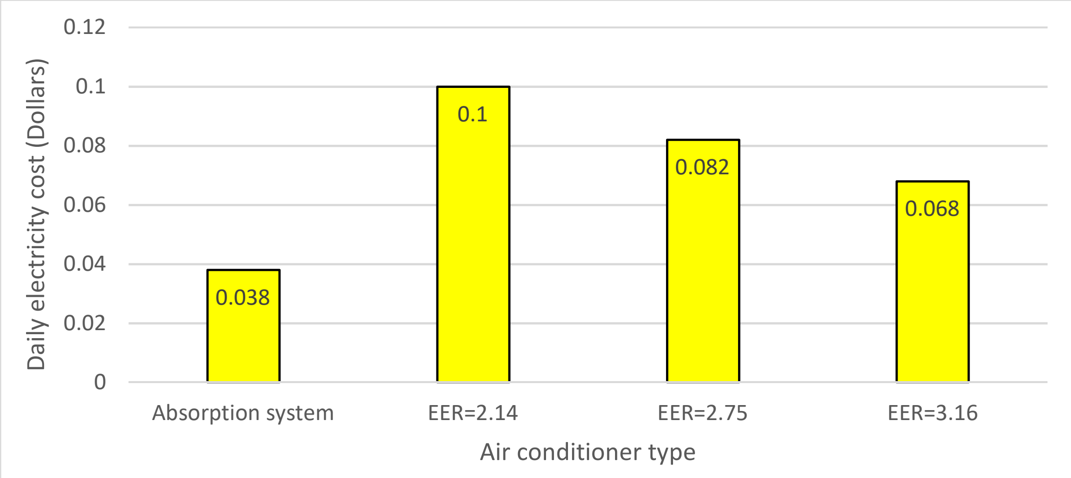

Figure 8: Daily cost of electricity consumed for absorption system and conventional chiller

Figure 9 shows the variation of daily total energy cost for the experimental days. The total energy cost is a summation of the cost of electricity used and the cost of gas used. The lowest cost can be observed to have been incurred on April 22 at \$ 0.61. This was due to the high solar fraction recorded which reduced the gas consumption and subsequently, the gas cost component of the total cost was low. June 6 also recorded a relatively low cost of \$ 0.69. This was due also to the relatively high solar fraction recorded on that day. The highest cost is observed to have been incurred on June 12 at \$ 1.21. This was because the system was powered on gas heating mode throughout the day, thereby increasing the gas cost component of the total cost. It can be inferred that it is more expensive to run the system on days with low or no solar fraction. More gas would be consumed on these days, due to the relatively high cost of the gas, the total cost would increase.

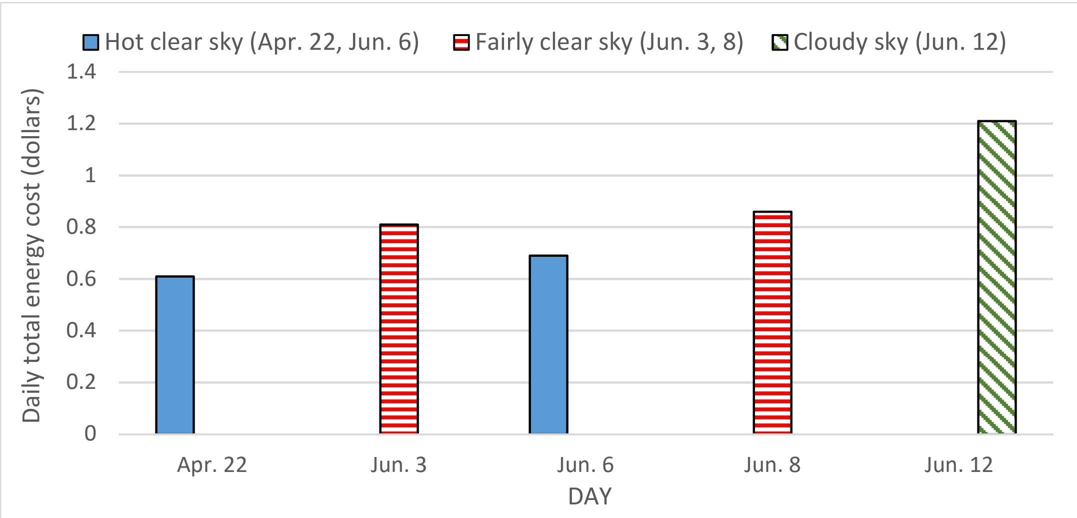

Figure 9: Variation of daily total energy cost for experimental days

Figure 10 shows the daily cost per kWh of cooling for the absorption air conditioning system in comparison with cost per kWh of cooling for conventional vapor compression chiller of varying energy efficiency ratio. From the figure, it can be observed that the cost per kWh of cooling for the absorption system varies with weather conditions. While it is low on hot clear sky days, it is higher on fairly clear sky days and highest on cloudy days. The lowest cost per kWh cooling for the absorption system was \$ 0.045, which was recorded on April 22. The highest cost per kWh cooling for the absorption system was \$

0.093, which was recorded on June 12. This indicates that it is more economical to run the absorption system on clear sky days with high solar radiation, while it is less economical to run the system on cloudy days with low solar radiation. The extra cost of gas that has to be incurred on cloudy days to run the system makes it less economical. On comparing with conventional vapor compression chillers of varying energy efficiency ratio, it can be observed that the cost per kWh of cooling for the conventional chillers is far less than that for the absorption system under any weather condition. This can be attributed to the additional cost of gas in the case of the absorption cooling system.

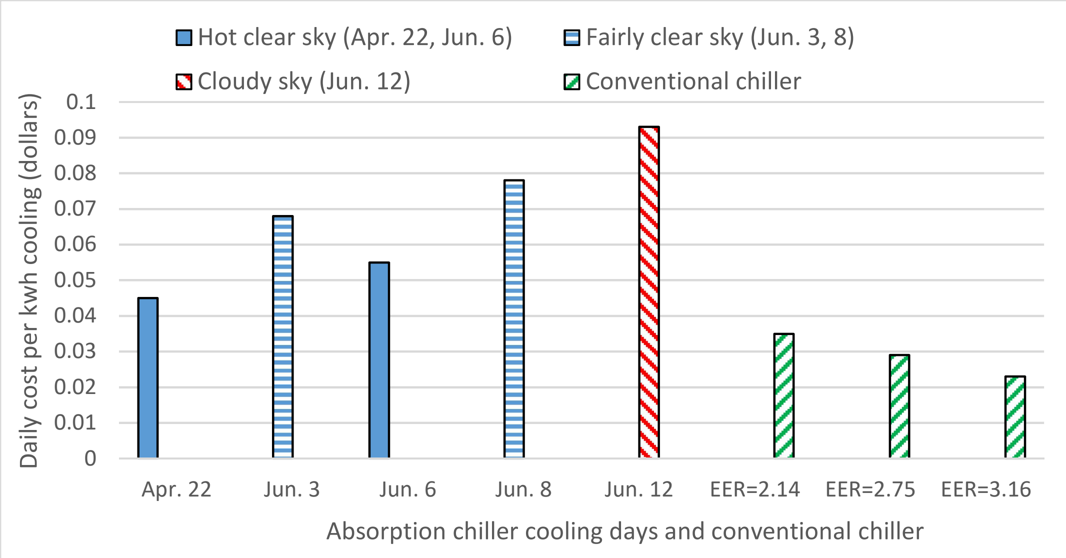

Figure 10: Daily cost per kWh cooling for absorption system and conventional chiller

4.0 CONCLUSION

The energy consumption and operating cost assessment of a solar and gas powered absorption air conditioning system under Zaria weather conditions has been carried out. Results from experiments carried out on the 3 kW cooling capacity system showed that electricity consumption is constant, while gas consumption depends on solar availability. Days with higher solar fraction require less gas consumption, while days with low solar fraction require high gas consumption. The cost per kWh of cooling was lowest on days with high solar fraction and highest on days with low or no solar fraction. The absorption air conditioning system has lower electric power consumption in comparison to the electric power consumption by conventional vapor compression chiller of same capacity. The reduction is in the order of 44.4% to 64.29%. However, the conventional vapor compression chiller has lower cost per kWh of cooling as compared to that of the absorption system. This is due largely to the extra cost of gas that has to be incurred to run the absorption cooling system.

REFERENCES

1. Kalkan N., Young E.A. and Celiktas A., 2012. Solar Thermal Air Conditioning Technology Reducing the Footprint of Solar Thermal Air Conditioning, *Renewable and Sustainable Energy Reviews*, 16: 6352–83.
2. Ghafoor A. and Munir A., 2015. Worldwide Overview of Solar Thermal Cooling Technologies, *Renewable and Sustainable Energy Reviews*, 43: 63–774.
3. Sarbu I. and Sebarchievici C., 2015. General Review of Solar Powered Close Sorption Refrigeration Systems, *Energy Conversion and Management*, 105: 403–442.

4. Henning H., 2007. Solar Assisted Air Conditioning of Buildings, An Overview, *Applied Thermal Engineering*, 27: 1734–49.
5. Al–Alili A., Islam M.D., Kubo I., Hwang Y. and Radermacher R., 2012. Modelling of a Solar Powered Absorption Cycle for Abu Dhabi, *Applied Energy*, 93: 160–167.
6. Sun H., Xu Z.Y., Wang H. and Wang R., 2015. A Solar/Gas Fired Absorption System for Cooling and Heating in A Commercial Building, *Energy Procedia*, 70: 518–528.
7. Zhai X., Li Y., Cheng X. and Wang R., 2015. Experimental Investigation on a Solar Powered Absorption Radiant Cooling System, *Energy Procedia*, 70: 552–559.
8. Albers J., 2014. New Absorption Chiller and Control Strategy for The Solar Assisted Cooling System at the German Federal Environment Agency, *International Journal of Refrigeration*, 39: 48–56.
9. Pongtorukulpanich A., Thepa S., Amornkitbamrung M. and Butcher C., 2008. Experience with A Fully Operational Solar Driven 10 ton LiBr/ H_2O Single Effect Absorption Cooling System in Thailand, *Renewable Energy*, 35(5): 943–9.
10. He T., Zhang X., Wang C., Wang M., Li B., Xue N., Shimizu K., Takahashi K. and Wu Y., 2015. Application of Solar Thermal Cooling System Driven by Low Temperature Heat Source in China, *Energy Procedia*, 70: 454–461.
11. Abdullah G., Saman W., Whaley D. and Belusko M., 2015. Optimization of Stand-alone Solar Heat Fired Absorption Chiller for Typical Australian Homes, *Procs. of the Intl. Conf. on Solar Heating and Cooling for Buildings and Industry*, 2–4 December, 2015, Istanbul, Turkey, 692–701.
12. Agrouaz Y., Bouhal T., Allouhi A., Kousksan T., Jamil A. and Zeraouli Y., 2017. Energy and Parametric Analysis of Solar Absorption Cooling Systems in Various Moroccan Climates, *Case Studies in Thermal Engineering*, 9: 28–39.
13. Demirel Y., 2012. *Energy, Green Energy and Technology*, Springer–Verlag, London Ltd., http://www.springer.com/cda/content [Accessed: 7 April 2018].
14. Duffie J.A. and Beckman W.A., 2013. *Solar Engineering of Thermal Processes*, 4^{th} Ed., John Wiley and Sons Inc., 111 River Street Hoboken, New Jersey, USA, 236–667.
15. Phadke A., Abhyankar N. and Shah N., 2014. *Avoiding 100 New Power Plants by Increasing Efficiency of Room Air Conditioners in India, Opportunities and Challenges*, Lawrence Berkeley National Laboratory, Berkeley, U.S.A., http://www.cseindia.org [Accessed: 25 July 2018].