Design and Modelling of Solar Energy System for Electrification for a Hospital in Saudi Arabia

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ABSTRACT

Electricity is crucial for delivering services such as lighting, equipment, HVAC systems, water heating, and communication. Refrigerators for vaccines and emergency surgery, laboratory, and diagnostic equipment are all require constant electricity supply. One of the largest users of electricity in the KSA are the healthcare centers. The objective of this paper is to design, model, simulate and analyze the performance of a solar PV panels system to supply health-care center by electricity that will be used for lighting, equipment, and air-conditioning. A selected health-care center is Al-Eis Health-Care Center (AHCC) in Al-Eis, Saudi Arabia, is considered as the case for the study. This health-care center needs approximately 162 kWh per day. 49 PV panels with 56 lead-acid batteries are enough to provide 72 kWh/day (for lighting and equipment operation). Energy is produced in the form of direct current (DC), and then converted to alternating current (AC) using an inverter. When the amount of available sunlight is minimal, a battery bank stores some of the DC power that may be utilized later. Extra power can be sold to the utility grid. In addition, a simulation of a solar absorption cooling system (SACS) is described in this study. This work was based on a single-stage absorption cooling machine powered by the NH3-H2O solution with cooling capacity of 15 kW. The COP for cooling system was determined to be 1.75 at T\text{in} = 90 \degree C. With an effective collector area of 28.41 m\(^2\), 14 evacuated-tube collectors are needed to be installed in two strings over the 84 m\(^2\) of backyard space in order to provide the necessary cooling. The cost for the entire PV panel and collectors' system was predicted to be 68,755 USD.

Keywords: Electrification, design and modeling, PV panels, solar collectors, solar energy system.

I. INTRODUCTION

Kingdom of Saudi Arabia (KSA) is a large country, covering 2.3 million square kilometers. KSA is a wealthy country. As a result, electricity demand is increasing at a rate of 5 % per year [1].

About 80 % of the population in capital cities and industrial areas has access to electricity thanks to the state power grid system. Extending the electrical power grid infrastructure into the Kingdom's sparsely inhabited areas is extremely expensive. As a result, many small remote communities need their own source of electrical energy. The applications of Renewable energy (RE) in KSA is not limited to fulfill the demands of isolated locations. Also, it will support the national grid handle summer peak load demand.

The need for additional medical centers and hospitals is rising in parallel with the population. The Ministry of Health operates 2,325 primary healthcare centers (PHCC) and 470 general and special hospitals with 70,844 beds. Large amounts of energy are used at these facilities regularly for lighting, air-conditioning, and equipment operation.

These hospitals and health-care centers takes its power demand either from grid system or using diesel generators.

Air conditioning systems based on mechanical vapor compression are frequently employed to provide a comfortable and revitalizing environment. Typically, the energy consumption of such systems is rather significant. Traditional vapor compression air conditioning systems have a high energy footprint that can be mitigated by switching to vapor absorption chillers powered by solar thermal energy or another renewable energy source. Aqua-ammonia and LiBr-H2O solar absorption cooling systems (SACS) have been the focus of much research.

The potential of employing solar thermal energy for space cooling was investigated by [2]. They covered 21 distinct sites around Saudi Arabia. The majority of the chosen sites have a daily solar irradiance higher than 6 kWh/m\(^2\) in the summer (April–September). This makes them very suitable locations for solar cooling applications.

This study aims to design a solar energy system for Al-Eis Health-Care Center (AHCC) that can clearly supply it by 100% of electricity for lighting and operating the equipment. Also, the number of PV panels and batteries, required to supply power to meet the specific design criteria, will be estimated. The study's secondary aim is to create a solar-powered HVAC system for AHCC. A single-stage SACS
II. LITERATURE REVIEW

A. Renewable Energy in Saudi Arabia

Despite its position as a major oil producer, Saudi Arabia is keen to participate actively to produce innovative technologies to explore and utilize renewables. Solar and wind are the most natural renewable energy sources that are freely available. The KSA expects to generate 30% of its electricity from renewables. Over the next decade, KSA hopes to invest over $20 billion in clean energy [3].

In January 2020, the Saudi Ministry of Energy initiated phase 3 of the National Renewable Energy Program (NREP). This phase involves 4 solar projects having a combined capacity of 1.2 GW. There will be a total of 2.17 GW of renewable energy capacity granted by the end of 2020. In 2019, 0.7 GW of that will be granted, while the remaining 1.47 GW will be awarded in 2020. By 2050, KSA plans to generate 30 GW of energy from renewables, according to National Grid CEO Ibrahim al-Jarbou, who spoke at a Siemens Energy Week virtual conference [3].

B. Solar Energy in Saudi Arabia

The vast majority of RE comes from the sun. Solar energy is recognized as a valuable and vital source that should be totally utilized for the benefit of Saudi Arabia. The solar radiation in KSA reaches 2.2 GWh per square meter. KSA is situated between 17.5°N-31°N latitudes and 36.6°E-50°E longitudes. Saudi Arabia lies in the Sunbelt region. It benefits from high levels of solar energy radiation (5.4-6.6 kWh/m²/day) as seen in Fig. 1). The daily sunlight hours are 8.89 hours (i.e., 3245 hours yearly). Around 6.22 kWh/m²/day (22.4 MJ/m²) is the average irradiation in KSA [4], [5]. These data indicate that KSA's possibilities to generate power from solar energy are great. Unfortunately, effective consumption of solar energy in Saudi Arabia has not yet made considerable progress due to the following barriers:

1) The plentiful supply of oil. Its dominance as a source of energy over solar energy, as well as its relatively low cost.
2) The effect of dust, which can decrease the amount of solar energy absorbed.
3) The government subsidies for oil and electricity generation are readily available, but comparable subsidies for solar energy projects are not. Solar energy would need incentive programs if such subsidies would continue.

C. Photovoltaic (PV) Technology

Photovoltaic (PV) panels use the photoelectric effect to directly transform the solar energy that strikes them into usable electrical current. The diffused radiation can be exploited by PV technology, making it applicable for either high or low irradiance regions.

When applied on a modest scale, solar PV technology has a long lifespan. Electricity generated by PV systems can either be fed into the current power grid or off-grid systems. The power generated by the system is sent through an inverter prior to being used. Some systems rely on batteries as a kind of emergency power storage. The size and complexity of a PV installation will influence its final price tag. A typical panel costs $250 and generates 300 W [7].

<table>
<thead>
<tr>
<th>Type of PV Panel</th>
<th>Efficiency (%)</th>
<th>Cost, (US$/W)</th>
<th>Area needed, (m²/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono-crystalline silicon</td>
<td>15-19</td>
<td>0.7</td>
<td>7</td>
</tr>
<tr>
<td>Poly-crystalline silicon</td>
<td>13-15</td>
<td>0.7</td>
<td>8</td>
</tr>
<tr>
<td>Amorphous silicon</td>
<td>5-8</td>
<td>0.8</td>
<td>15</td>
</tr>
</tbody>
</table>
The vast majority of solar arrays are installed on rooftops. PV panels can be ground-mounted or integrated into a shade structure if there is no suitable roof space. Shading has a negative impact on photovoltaic arrays. When building collector arrays, shading is a big issue since collectors may block each other out and reduce the amount of solar energy that reaches the system. Solar photovoltaic (PV) systems work best when they get unimpeded, direct sunlight from around 9 a.m. to 3 p.m., every day of the year. Remember that different times of the day can make the same spot either shady or sunny. A spot that is in the shade during the summer will also be in the shade during the winter since winter shadows are longer [8].

The PV panels' inclination (tilt) and the system's geographic orientation both impact the quantity of solar energy received by the system (orientation). Panel orientation is crucial for optimizing the performance of a solar collector. In the Northern Hemisphere, solar panels should be pointed at true south (an azimuth of 180 degrees). The optimal tilt of a PV array, in terms of annual maximum power output, is typically equal to the latitude minus roughly 15 degrees. Power generation is maximized in the winter at a greater tilt, and in the summer at a lower tilt [8].

2) Batteries

The power generated by solar PV panels may be stored in batteries for usage during the day and night, even on cloudy or overcast days. A group of batteries in series or parallel is called a battery bank. In some cases, a battery is not required. Some systems, called "on-grid", neglect batteries in favor of the power grid itself.

The two most prevalent kinds of batteries are lead-calcium and lead-antimony. The nickel-cadmium battery is another option, especially when the battery will be exposed to a broad temperature range. Due to the sporadic nature of solar radiation, batteries should be able to resist several charge and discharge cycles. The battery's type determines the maximum current that may be drawn from it before the battery is damaged. Lead-calcium batteries are best used in the situations where the depth of discharge (DOD) never exceeds 80% [9].

Batteries are characterized by their voltage (V) and capacity (Ah). For instance, under standard conditions, a battery of 100 Ah and 48 V will store 100 Ah × 48 V = 4800 Wh of electricity. The voltage of battery is a multiple of 12 V (i.e., 12 V, 24 V, and 48 V) [9].

The degree which a battery will be discharged with respect to the total capacity is referred to as DOD. A 200 Ah battery with a 60 % DOD, for example, has an 80 Ah capacity remaining of the stored energy.

Days of autonomy (DOA) for a battery refers to the number of days a fully charged battery will meet load demand if the PV system does not feed the battery. DOA usually takes between 2 and 5 days.

3) Solar Charge Controller (SCC) and DC/AC Inverter

Controller are used to regulate the flow of electricity from the battery to the load. It is important to use a solar charge controller (SCC) to: (i) controls the amount of energy supplied by the PV panels to the battery bank; (ii) stops the batteries from being overcharged; and (iii) keep the batteries viable for a longer period of time.

An inverter is needed to change the direct current (DC) electricity generated by the PV modules into alternating current (AC). It's not necessary to use an inverter with every system. An inverter is unnecessary, for instance, in systems with no AC load.

E. Absorption Cooling System (ACS)

Absorption refrigeration was one of the early cooling methods. Michael Faraday discovered vapor absorption while reducing gases to liquids in 1824. Ferdinand Carre invented absorption refrigeration in 1860. This cooling system works for homes and businesses. Ammonia refrigerates absorption refrigeration systems. Absorption systems use heat energy instead of mechanical energy to change the refrigerant's conditions [10].

In an absorption cooling system, two chemicals are brought together from distinct phases to produce a solution. The conditions of heat and pressure are critical to this procedure. The liquid absorbent takes up the refrigerant vapor when the temperature and pressure are low and gives it back when they are high. It is illustrated in Fig. 3 how the basic absorption cooling system operates.

Ammonia vapor is released from the evaporator and transported to the absorber, where it is cooled by the water. Large quantities of ammonia vapor may be absorbed by water, creating a solution known as aqua-ammonia. Water's ability to soak up vaporized ammonia increases the solution's temperature by allowing more ammonia to be extracted from the evaporator at a given pressure. Water cooling systems are commonly utilized to reduce the heat of solution generated by the absorber. At higher temperatures, water has smaller ability to absorb ammonia vapor. In order to transport the solid solution created by the absorber to the generator, a liquid pump is required. The pressure of the solution is increased to a maximum of 10 bar by the pump [10].

Fig. 3. Simple absorption cooling system (ACS) [10].

The generator uses an outside fuel source like gas or steam to heat a concentrated ammonia solution. During the heating process, the ammonia vapor is forced out of the solution under high pressure, leaving a hot, weak ammonia solution in the generator. The low-pressure ammonia solution flows back to the absorber after passing through the pressure-reducing
valve. After going through a pressure lowering valve, this dilute ammonia solution returns to the absorber at a low pressure. The very pressurized ammonia in the condenser, the ammonia vapor from the generator is turned into a high-pressure liquid. A liquid ammonia supply is sent to the expansion valve and finally the evaporator.

F. Solar Absorption Cooling System (SACS)

The ammonia and water (NH₃-H₂O) solution is heated using solar collectors. The condenser is where the water vapor changes phase by losing its heat to the surrounding environment after being separated. After passing through a pressure-reducing throttle valve, the superheated liquid water is finally ready to be transported to the evaporator, where it will evaporate and be used to chill the surrounding environment. The water vapor from the evaporator is absorbed by the generator's strong solution (rich in NH₃), causing heat that must be released. By repeatedly pumping the dilute fluid, the generator is able to renew (low in NH₃). One way to boost the cycle's efficiency is to install a heat exchanger between the generator and the absorber to pre-heat the weak solution and lower the generator's energy needs.

G. Solar Collectors

Sunlight is converted into usable heat by solar collectors. Selecting the appropriate collector for a specific application is dictated by the range of the operating and surrounding temperatures.

Each collector has a peak temperature at which it performs optimally. The evacuated-tubes collectors (ETCs) are used to heat water up to 177 °C, while in the parabolic trough collectors, the water can be heated up to 299 °C [11].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average daily irradiance, G</td>
<td>6.22 kWh/m²</td>
<td>[4]–[5]</td>
</tr>
<tr>
<td>Peak sun hours (PSH)</td>
<td>6.22 hours</td>
<td>[4]–[5]</td>
</tr>
<tr>
<td>Mean ambient temperature, T_a</td>
<td>29°C</td>
<td>Weather Stations</td>
</tr>
<tr>
<td>Clearness index, k</td>
<td>0.8</td>
<td>[9]</td>
</tr>
</tbody>
</table>

III. METHODOLOGY

In this section we will give a technical overview of the system components. Also, design methods and mathematical calculations for sizing these components are also represented.

A. About the Al-Eis Health-Care Center (AHCC)

AHCC is located in 25.075 ºN latitude and 38.122ºE longitude. The data in Table II about this location are used in our study.

It was presumed that during work time, all lights, HVAC, and other devices and equipment are working. The AHCC is open for 5 days a week. The center starts working from 8:00 to 16:00. During the month of Ramadan, the center works in two shifts (10:00-14:00 and 20:00-00:00).

The study's goal is to assess the viability of a solar systems as sources of power for the facility's lighting, HVAC, and other electrical needs.

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Description</th>
<th>Power Consumption (kWh/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>Total electrical power load consumed by normal lightings.</td>
<td>10</td>
</tr>
<tr>
<td>Equipment</td>
<td>All medical devices, TVs, fans, pumps, ... etc.</td>
<td>62</td>
</tr>
<tr>
<td>Total Daily Load (L)</td>
<td></td>
<td>72</td>
</tr>
</tbody>
</table>
3) Solar charge controllers (SCC).
4) DC to Ac inverter.
5) Connections and wiring.

C. PV System Design

The system design calculations are conducted by the following steps:
1) Estimating total load. The total load of AHCC (including lighting, equipment, and air conditioning) are to be calculated.
2) Sizing the solar PV system. This includes selecting the type of PV panels, number of panels, arrangement of PV array, and the orientation of panels (i.e. tilt angle).
3) Sizing the battery bank.
4) Sizing the Inverters.
5) Sizing the solar charge controller.

1) Estimating Total Daily Load

The total load includes all electrical appliances such as lighting and equipment that are connected to the solar PV system. The total daily load is estimated by assuming the hospital’s total power usage (kWh/day) as shown in Table III.

2) PV array Sizing

Standard Testing Conditions (STC) involve 1 kW/m² of irradiation and a PV cell temperature of 25°C. These conditions are used to determine a PV module’s rated power output. The characteristics of selected PV modules are represented in detail in Appendix A.

a) Method 1: Exact Design (RETScreen [9])

The process of electricity production and transmission is represented in Fig. 7.

The PV panel is characterized by its average efficiency, $\eta_p$, which is a function of average panel temperature

$$\eta_p = \eta_p \left(1 - \beta_p (T_p - T_r)\right)$$  \hspace{1cm} (1)

where $\eta_p$ is the PV panel efficiency at $T_p$, $T_r$ is the reference temperature (25 °C). $\beta_p$ is the temperature coefficient for module efficiency. The values of $\eta_p$ and $\beta_p$ are taken from Appendix A as 20.1 % and 0.0038/°C, respectively. $T_p$ is a function of the ambient temperature as given in (2).

$$T_p - T_r = \left(219 + 832\overline{k}\right) \left(\frac{NOCT - 20}{800}\right)$$  \hspace{1cm} (2)

where $\overline{k}$ is the clearness index. It ranges from 0.3 (for cloudy areas) to 0.8 (for sunny areas). NOCT is the Nominal Operating Cell Temperature (NOTC = 45 °C). From (1) and (2), we have $T_p = 56.6$ °C and $\eta_p = 17.7%$.

The total area $S_A$ of the PV panel array can be calculated as

$$S_A = E_d / (\eta_p G) = (E_d) / (\eta_p \eta_m \eta_s G)$$  \hspace{1cm} (3)

where $E_d$ is the energy provided by the PV array, $E_d$ is the energy provided by the PV array after battery bank ($E_d$ equals the daily load demand 70 kWh), $G$ is the daily irradiance (6.22 kWh/m²), $\eta_G$, $\eta_B$ and $\eta_I$ are the efficiencies of controller, batteries, and inverter, respectively ($\eta_G = 95\%$, $\eta_B = 90\%$, $\eta_I = 96\%$). Hence, the total area of solar panels $S_A = 79.7$ m². The area $S_p$ of a single PV panel is (1.56 m × 1.05 m). So, the number of PV panels is 49 according to (4).

$$n = S_A / S_p$$  \hspace{1cm} (4)

b) Method 2: Approximate Design

The energy required from the PV panel array, which is the daily consumption or the total daily load ($L_t$), is 72 kWh. The Peak sun hours (PSH) also equal 6.22 hours. Therefore, PV panels array power is dividing the energy required from the PV panel array over the PSH as following

PV panels array power = (72 kWh)/(6.22 hours) = 11.576 kW = 11576 W.

The number of PV panels ($n$) is calculated by dividing this power of PV over the rated power of a single PV panel. The rated power of the PV panel (from Appendix A) is 327 W. Therefore, $n = (11576 W)/(327 W/panel) = 35.4$. So, we can use 36 PV panels.

Note: The estimated number of panels by method 1 is greater than that by method 2. So, method 1 is approved. In addition, the first method is more accurate because it takes into account many parameters.

The 49 PV panels is arranged in 7 strings (parallel rows), and 7 panels in series. When installing several rows of PV panels in series behind each other, suitable clearance to prevent shading must be maintained. For this purpose, the minimum clearance (distance) required between each row of
panels must be calculated. This is represented by distance \((d)\) in Fig. 8. This distance can be calculated using (5) [12].

\[
d = h \left[ \left( \sin(180^\circ - \beta - \gamma_s) \right) \right] / \left( s s y \right)
\]

(5)

Determining this clearance requires the angle \(\gamma_s\) of the sun at mid-day in the shortest day of the year (i.e., 21st December) [8]. In Al-Eis, that angle is 41.5° (see Fig. 9). The tilt angle used is \(\beta = 15°\). Hence, the distance \(d \approx 2\text{m}\).

![Fig. 8. Clearance Between Collectors or PV Panels Rows.](image)

![Fig. 9. Angle \(\gamma_s\) of the sun at mid-day in the shortest day of the year (21st December) for Al-Eis area (by Solar elevation angle Calculator, keisan.casio.com).](image)

3) Battery Bank Sizing

The charging load "L", the number "N" of days of autonomy (DOA), the maximum DOD "D" are used to determine the optimal battery size [7]. The suitable capacity of battery bank is calculated using (6).

\[
Q_b = I \times V = \frac{L \times N}{D \times \eta_b}
\]

(6)

where \(Q_b\) is battery bank capacity (in kWh or Wh), I is battery bank capacity (in Ah), V is system voltage, and \(\eta_b\) is the battery efficiency. For batteries bank design, the following two parameters are considered: an average battery's efficiency of 90%, and two autonomy days. The depth of discharge for Lead-Acid Batteries is 50%. The general rule of thumb is that the greater the shelter's energy needs, the higher the voltage requirements of the solar PV system. Because of this, the system's voltage was selected to be 48 V. The type of battery used in this study is (Jingsun 12 V 250 Ah Deep Cycle Battery). Hence, the capacity of battery bank (for 48 V system voltage) is 3333 Ah. Also, the number of batteries connected in series is calculated by dividing the system voltage over the rated voltage of a single battery. So, we need 4 batteries in each row (i.e., 4 batteries in series). In addition, the number of strings (or rows) is calculated by dividing the battery bank capacity (3333 Ah) over the rated capacity of a single battery (250 Ah). The number of strings is estimated as 13.33, but we can use 14 strings. As a result, 56 batteries are required.

4) SCC Sizing

After sizing the battery bank and PV array, your next step is to size the charge controller. The most common controller choice is the maximum power point tracking (MPPT) controller.

The nominal voltages of the solar array and the battery bank must be compatible with the controller's DC voltage input. Additionally, the controller's amperage rating should be double the maximum current expected to flow from the PV system. The charge controller's rated power is greater than the maximum power the PV array could produce since a safety factor of 1.2 is used. The following are the steps to choose an SCC: [13]

1) Wattage of the PV array = (number of PV panels) \times (PV panel rated power) = 49 panels \times 327 W/panel = 16,023 W = 16 kW.

2) Rated voltage of SCC = (number of panels in series) \times (Voc of panel) = 7 panels \times 64.9 V/panel = 454.3 V.

3) Rated current of SCC = (number of strings of panels) \times (Isc of PV panel) \times (safety factor) = 7 panels \times 6.46 A/panel \times 1.2 = 54.5 A.

By operating like a DC stepdown transformer, an MPPT controller allows the array to be run at a much greater voltage than is really needed to provide the desired output. Since there will be less current flowing through the array's wiring, you can utilize less heavy, less expensive wire, and/or reduce wiring losses.

5) DC/AC Inverter Sizing

Sizing the inverter is the last step in designing a solar PV system. To avoid overloading the inverter, we must take into account the total electrical load of all of the appliances while making our inverter selection. For AHCC, this maximum power is about 12 kW. Therefore, the rated power of the inverter should be greater than 12 kW.

D. Solar Absorption Cooling System (SACS)

The SACS comprises two circuits: (a) the cooling circuit, and (b) the solar heating circuit.

The proposed SACS is shown in Fig. 10. The desorber in ACS is heated by solar energy captured by the ETC.

The chiller is the heart of the SACS, and it uses an ammonia-water combination (NH3-H2O). See Fig. 10 for a layout of its components: evaporator, generator unit, condenser, absorber, expansion valves, and pump.

1) Cooling Circuit Calculations

The cooling load of the AHCC is approximately 15 kW. If the cooling process is assumed to work for 6 hours per day, then the cooling load can be given as (15 kW \times 6 hours/day = 90 kW/h/day). Steady periodic conditions are assumed. Also, the following assumptions are used in the analysis of the ACS [14], [15]:

DOI: http://dx.doi.org/10.24018/ejenergy.2023.3.2.106
1) The pressure of the generator and the condenser are identical.
2) The pressure of the evaporator and the absorber are identical.
3) The vapors leaving the generator are slightly superheated.
4) The refrigerant leaving the condenser is saturated liquid water.
5) The streams leaving the evaporator, absorber, generator, and condenser are saturated (i.e., points 1, 2, 4 and 7 in Fig. 10).
6) The temperature in the evaporator, generator, absorber, and condenser are 90°C, 7°C, 35°C, 35°C, respectively.
7) The temperature difference of the cooled air in the evaporator is $\Delta T_{a,i} = 15$°C.
8) The temperature difference of the cooling water in the condenser (and the absorber) is $\Delta T_{c,w} = 5$°C.
9) The temperature difference of the heating water in the generator is $\Delta T_{h.w} = 30$°C.
10) The weak solution is assumed to be free of ammonia (only water).
11) The temperature of heating water (from the heating circuit to the generator) is controlled to be 95°C. This heating water, also, is controlled to exit the generator at 70°C.

The amount of heat supplied to the refrigerant by the generator, denoted by $Q_G$, is the amount of heat absorbed by the refrigerant in the evaporator. It is calculated by (8). Theoretically, it should be equivalent to the cooling load of the room being conditioned (i.e., $Q_E = 15 \text{ kW}$).

$$ Q_E = \dot{m}_{\text{NH}_3} \left( h_1 - h_3 \right) = \dot{m}_{\text{w}} C_{P,\text{w}} \Delta T_{\text{air}} $$

$h_1$ and $h_3$ are the specific enthalpy of ammonia at point 1 and 8, respectively, and can be estimated from the chart in Fig. 10.

b) In the evaporator:

The heat discharged to the atmosphere (or cooling water) is determined by (9).

$$ Q_G = \dot{m}_{\text{NH}_3} \left( h_6 - h_7 \right) = \dot{m}_{\text{w}} C_{P,\text{w}} \Delta T_{\text{air}} $$

$c)$ In the condenser:

The heat, $Q_C$, rejected to the atmosphere (or cooling water), is calculated using (12).

$$ Q_C = \dot{m}_{\text{NH}_3} \left( h_8 - h_5 \right) = \dot{m}_{\text{w}} C_{P,\text{w}} \Delta T_{c,w} $$

$d)$ In the absorber:

The heat discharged to the atmosphere (or cooling water) from the condenser, and is calculated as

$$ Q_{A} = \dot{m}_{\text{NH}_3} \left( h_3 + m_{\text{w}} h_8 - m_{\text{w}} h_5 \right) $$

$e)$ In the generator:

The heat given to the refrigerant in the generator, and is calculated using (9).

$$ Q_G = \dot{m}_{\text{NH}_3} \left( h_4 + m_{\text{w}} h_4 - m_{\text{w}} h_3 \right) $$

$$ CR = m_{\text{w}} / \dot{m}_{\text{NH}_3} $$

$f)$ In the condenser:

The heat delivered to the solar heating circuit (solar collectors) and auxiliary heater and is equal to $m_{\text{w}} (h_9 - h_2)$.

$$ Q_C = \dot{m}_{\text{NH}_3} \left( h_5 - h_7 \right) = \dot{m}_{\text{w}} C_{P,\text{w}} \Delta T_{c,w} $$
Fig. 10. Solar absorption cooling system (SACS).

Fig. 11. Energy and mass balance diagrams.

**In the absorber:**

\( Q_A \) is the heat discharged to the atmosphere (or cooling water) from the condenser, and is calculated as

\[
Q_A = m_{\text{sat,3}} h_1 + m_{\text{sat}} h_5 - m_{\text{sat}} h_2
\]  

(13)

\( h_1 \) is the specific enthalpy of ammonia at point 1. \( h_5 \) is the specific enthalpy of weak solution (assumed as water) at point 5, while \( h_2 \) is the specific enthalpy of strong solution (mixture of ammonia and water) at point 2.

\( Q_P \) is the heat added to the refrigerant due to the pump working. This heat is neglected.

According to the second law of thermodynamics, we have

\[
Q_G + Q_E = Q_C + Q_A
\]  

(14)

The coefficient of performance (COP) of the cooling circuit is given in (15), while the maximum possible COP for the cooling circuit is given in (16).

\[
COP = \frac{Q_E}{Q_G}
\]  

(15)

\[
COP_{\text{max}} = \frac{T_G (T_G - T_d)}{T_G - T_E} \left( \frac{T_C}{T_A} \right)
\]  

(16)

The exergy destruction for all components is given by (17):

\[
I = T_{in} \left[ \sum m_{\text{sat}} s_{\text{sat}} - \sum m_{\text{sat}} s_{in} \right]
\]  

(17)

where \( T_{in} \) is constant (\( T_B = 221 \text{ K} \)). From the chart (in Fig. 12), we can estimate the following:

1. The specific enthalpy and specific entropy of saturated ammonia vapor at 90°C is 1450 kJ/kg (i.e., \( h_6 = 1450 \text{ kJ/kg} \)) and \( s_6 = 4.62 \text{ kJ/kg.K} \).
2. The specific enthalpy and specific entropy of saturated ammonia liquid at 35°C is 350 kJ/kg (i.e., \( h_7 = 350 \text{ kJ/kg} \)) and \( s_7 = 1.6 \text{ kJ/kg.K} \). Also, \( h_8 = h_Y = 350 \text{ kJ/kg} \), \( s_8 = 1.58 \text{ kJ/kg.K} \).
3. The specific enthalpy and specific entropy of saturated ammonium vapor at 7°C is 1455 kJ/kg (i.e., \( h_1 = 1455 \text{ kJ/kg} \)) and \( s_1 = 5.4 \text{ kJ/kg.K} \).
So, the mass flow rate of ammonia, cooling water, and cooled air can be estimated as 0.01357 kg/s, 0.711 kg/s, and 0.995 kg/s, respectively.

The mass flow rate of heating water from the storage tank (or from collectors’ array) should not be more than 15 L/min per row of collectors (according to the collectors’ datasheet). So, we will use \( \dot{m}_{h,w} = 15 \, 	ext{L/min} = 0.25 \, \text{kg/s} \). Therefore, we can use (18) to calculate \( Q_G \).

\[
Q_G = m_{h,w} \left( h_1 - h_2 \right) \tag{18}
\]

where \( h_1 = 397.96 \, \text{kJ/kg} \) and \( h_2 = 292.98 \, \text{kJ/kg} \) are the specific enthalpy of heating water at 100°C and 70°C, respectively [19]. As a result, the value of \( Q_G \) is 26,245 kW. From the above calculations, the coefficient of performance (COP) of the cooling system is 1.75.

2) Solar heating Circuit Calculations

We can estimate collector’s size using (19):

\[
A_c = \frac{Q_G}{\eta_{\text{solar}} G_{\text{max}}} \tag{19}
\]

where \( A_c \) is the total collector area (m²), \( \eta_{\text{solar}} \) is the efficiency of solar heating circuit. We have used a value of 0.6 for \( \eta_{\text{solar}} \) in our analysis. The highest daily solar radiation is denoted by \( G_{\text{max}} \) (6.6 kWh/m²/day). If \( G_{\text{max}} \) is used in the equation above, then the system is built to handle the peak demand on the sunniest day of the year, which reduces wasteful capacity and maximizes efficiency [20].

Since \( Q_G \) is 26,245 kW (157.5 kWh), the required area of collector is 39.77 m².

The calculations and modeling of the proposed SACS will use the ETC (type AP-30). Appendix B includes a comprehensive breakdown of the collector performance characteristics. Since the aperture area of one collector is 2.82 m², then, the number of collectors required is 39.77 m² / 2.82 m² = 14.1. Therefore, 14 solar collectors will be selected.

These collectors can be arranged in two strings (i.e., 7 collectors in series).

When installing several rows of solar collectors in series behind each other, suitable clearance to prevent shading must be maintained (as explained in PV panels arrangement).

E. Performance Analysis

It is not always sufficient to just design and pick the optimal configuration; other performance aspects should be assessed as well. A solar off-grid PV system's Performance Ratio (PR) is essential since it shows how closely the system's actual performance matches the theoretical performance. Performance Ratio of the whole solar system is calculated using (20).

\[
PR = \frac{\text{UsefulEnergy(kWh)}}{\frac{\text{SolarIrradiance(kWh/m²)} \times \text{PV Array Area(m²)}}{}} \tag{20}
\]

F. Cost Analysis

The system's economic performance can be handled by hand. The first outlay covers everything from purchasing materials to hiring a crew to put it all together. The pricing of the components has been collected from supplier and manufacturer websites. A detailed investment cost is shown in Table IV.

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Unit Cost, ($US/unit)</th>
<th>Total Cost, ($US)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Panel</td>
<td>49</td>
<td>377</td>
<td>18,473</td>
</tr>
<tr>
<td>Solar Charge Controller (SCC)</td>
<td>1</td>
<td>1,285</td>
<td>1,285</td>
</tr>
<tr>
<td>Batteries</td>
<td>56</td>
<td>175</td>
<td>9,800</td>
</tr>
<tr>
<td>Inverter</td>
<td>1</td>
<td>2,056</td>
<td>2,056</td>
</tr>
<tr>
<td>DC CB</td>
<td>3</td>
<td>30.22</td>
<td>90.66</td>
</tr>
<tr>
<td>AC CB</td>
<td>1</td>
<td>24.5</td>
<td>24.5</td>
</tr>
<tr>
<td>SPD</td>
<td>1</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>DC Isolator</td>
<td>1</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Connections and cables</td>
<td>200 m</td>
<td>$US 0.46/m</td>
<td>92</td>
</tr>
<tr>
<td>Solar Collectors</td>
<td>14</td>
<td>2,000</td>
<td>28,000</td>
</tr>
<tr>
<td>Storage Tank</td>
<td>1</td>
<td>3,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Cooling Chiller</td>
<td>1</td>
<td>4,500</td>
<td>4,500</td>
</tr>
<tr>
<td>Piping</td>
<td>40 m</td>
<td>$US 32.35/m</td>
<td>1,294</td>
</tr>
<tr>
<td>Total Cost ($US)</td>
<td></td>
<td></td>
<td>68,755.16</td>
</tr>
</tbody>
</table>

IV. SIMULINK MODELING AND SIMULATION

In this section the MATLAB/Simulink software is used to study the performance of the designed system.

The 16 kW PV array consists of 7 strings of 7 series-connected 327 W modules connected in parallel (7 × 7 × 327 W = 16,000 W). The output of PV array and battery bank are shown in the following Fig. 14.

V. NUMERICAL RESULTS AND DISCUSSION

Table V and Table VI below show the summaries of sizing the PV panels and collectors systems. Average solar irradiation was taken from Al-Eis weather data. The total daily loads were 72 kWh for lighting and equipment operation, and 90 kWh for air-conditioning. The number of PV panels obtained from calculations is 49 with a total aperture area of 79.7 m². The SunPower PV panels are more efficient and selected to supply the AHCC. PV panel specifications are also shown in Table V.
For a maximum utilization from the installed capacity of panels, they will face south with an inclination of 15°. The 49 PV panels are arranged in 7 strings (rows), and 7 panels in series. The area required for panel installation is 165 m² (11 m × 15 m).

The type of batteries used in this study was Jingsun 12V 250 Ah lead acid batteries, with total capacity of 3333 Ah (for 48 V system voltage). For the proposed system, we need only one controller (16 kW) and only one inverter (16 kW is appropriate).

The system was designed based on operation days of 260 days/year (5 days a week). That mean we have 2 day a week with no operation (Thursday and Friday), and this is enough time to charge the battery bank. So, DOA was taken to be 1.

The operation of a SACS was designed to provide cooling for AHCC having a cooling load of 15 kW. The system consisted of a NH₃-H₂O Yazaki absorption machine with a nominal cooling capacity of 15 kW, with a 2.5 m³ hot storage tank. An auxiliary heater of a heating capacity of 3 kW may be used as a backup system.

The nominal cooling capacity of the system was 15 kW. This system includes a Yazaki absorption machine and a 2.5 m³ storage tank. As a backup, a 3 kW auxiliary heater can be utilized.
VI. CONCLUSION

This research investigates the potential of solar PV system in the reduction of fuel consumption for AHCCs, in Saudi Arabia.

The solar PV panels should be tilted by an angle of 11° to south through the whole year. In order to have the maximum possible amount of solar radiation and minimum optical losses, a tracking system should be used.

Scope for further research may also include the analysis of the ease of installation, operation and maintenance of such a system.

Performance ratio of the whole PV solar system is about 14.5%. The total cost required to install 72 kWh/day PV system and 90 kWh/day cooling system is about US$ 68,755.

APPENDIX

A) SunPower E20 PV panel specifications:

<table>
<thead>
<tr>
<th>Key Material Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Sheet</td>
</tr>
<tr>
<td>Front Glass</td>
</tr>
<tr>
<td>Frame</td>
</tr>
<tr>
<td>Edge</td>
</tr>
<tr>
<td>Size</td>
</tr>
</tbody>
</table>

B) Apricus AP-30 solar collector specifications:

<table>
<thead>
<tr>
<th>Key Material Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
</tr>
<tr>
<td>Grounding</td>
</tr>
<tr>
<td>Frame</td>
</tr>
<tr>
<td>Heat Transfer Fluid</td>
</tr>
<tr>
<td>Back Sheet</td>
</tr>
<tr>
<td>Size</td>
</tr>
</tbody>
</table>

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REFERENCES


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He received the bachelor's degree in mechanical engineering from College of Engineering, Taibah University, Saudi Arabia. Then he pursued a master's degree in Mechanical Engineer and renewable energy at Umm Al-Qura University. During his master's program, He focused on the design and optimization of solar systems, and his thesis work was on the development of a solar desalination system.

Mr. Bakheet has a paper that was published in a peer-reviewed journal. That paper was a study that proposed and investigated an innovative design of solar natural vacuum desalination (SNVD) system.