INTRODUCTION

The energy demand is increasing, and environmental impacts are also becoming a serious threat to the world. The emissions of CO₂ and other greenhouse gases (GHG) are contributing to global warming. These emissions are also a significant contributor to climate change. Global warming has made all the seasons changed just like summers are getting hotter and hotter. In Qatar, it is getting hotter and more humid, which makes it nearly impossible to walk freely to access public transportation in summers. To overcome this problem, there is a need to provide self-sustaining shelters, which can facilitate the resting of the public. In Qatar, on-site use of solar energy is favored to

Abstract

To overcome the problem of walking in the scorching heat and to encourage people to use more public transport (ie, trams and metros), the idea of sustainable climate refuge shelter is highly needed. In this study, the proposed shelter includes semi-transparent photovoltaic cells located on the roof integrated with batteries to keep the system running at nighttime and in unfavorable irradiation conditions. An atmospheric water generator for freshwater production is employed for drinking and water misting in addition to a vapor compression cooling system with a fan. Freshwater is collected by extracting water from humid air through cooling with dehumidification. The system is analyzed thermodynamically through energy and exergy efficiencies. The overall energy and exergy efficiencies of the system are 19.45% and 9.58%, respectively. The electrical efficiency of the photovoltaic cells decreases from 16.87% to 15.24% with an increase in cell temperature from 309 K to 315 K. Hourly analysis of the proposed system for the whole year is performed to evaluate the energy profile. The proposed system generates electricity in winters that is sufficient to keep the system operational for 2 days (only for drinking water requirement), but in the summers, only 24 h due to extensive cooling load. The effects of several parameters such as irradiance, ambient temperature, relative humidity, transmittance, and occupancy rate are studied.

KEYWORDS

freshwater, humid air harvesting, solar photovoltaic, space cooling, vapor compression
be employed in the off-grid designs as the country’s direct normal irradiance (DNI) is about 2,008 kWh/m²/year and thus average energy received is 5.5 kWh/m².³

Semi-transparent solar cell technology can be deployed to combine the visible light transparency and the conversion of light into electricity. This technology can be integrated into windows and sky-light within sustainable buildings.⁴ Miyazaki et al.⁵ have shown in their study that 55% of the electricity can be saved in buildings by using optimum photovoltaic (PV) windows. Shukla et al.⁶ found out that the energy efficiency of the semi-transparent PV varies between 11% and 18% when installed on the roof and 13% and 18% at the facade throughout the day. Roof carrying capacity and accessibility for PV panel installation, maintenance, and repairs can restrict the installation of conventional solar PVs. Also detailed shading loss analyses reveals a reduction of more than 20% of power yield by building integrated semi transparent photovoltaic (BISPV).⁷ The report by⁸ explains about the partially and fully integrated roofs, also large- and small-sized solar roofs are being in the discussion. The solar cell needs direct or indirect light to keep producing electricity for the loads during the daytime. A storage unit like a battery should be attached to the system to supply enough power to drive the system during nighttime. Battery-based renewable energy applications use the batteries to be charged and discharged in an unpredictable manner depending on sunlight and seasonal variations.⁹ The correct size of the battery is important in providing energy in an adequately and timely manner. Over- or undersizing of the storage batteries can lead to low reliability or high cost (operational and maintenance cost).¹⁰ The PV battery system size optimization for off-grid housing is determined upon building design, operation, installed PV capacity, and local climate.¹¹

To make the systems off-grid, efficient approaches have been used such as considering suitable renewable sources with optimized size of battery; for example, Tsiaras et al.¹² first analyzed the suitable renewable techniques for the selected region, and then, the data to support the off-grid operation of small settlements were gathered. The study showed that the design, analysis, and integration of the off-grid small settlements by renewable techniques for energy production are feasible. Ren et al.¹¹ worked to evaluate the feasibility of an off-grid operation of fully electric housing by employing solar PVs and by considering different operational scenarios (for daytime and evening time) and reported the payback period of 12 years and 15.8 years of discounted payback period for the considered system. Ishaq et al.¹³ also designed an off-grid PV system along with batteries to meet the electrical energy demand of the considered building, which includes lighting bulbs, refrigerators, fans, computers, and TVs to meet the daily requirement of 48.787 kWh/day. Hassan¹⁴ also designed two systems, namely off-grid and on-grid photovoltaic power system to meet the electrical load of households with higher penetration of renewable resources and lower CO₂ emissions. The study showed that renewable resources when combined with on-grid are beneficial to feed the grid as well showing lower net present cost and cost of energy. To save the grid from the adverse effects of rapid load fluctuation and also fluctuation of solar irradiance, Jaszczer and Hassan¹⁵ proposed an on-grid energy system with supercapacitors. In this study, supercapacitors found to be most promising, having cheap maintenance, long-term reliability, and a very high current in a short time to stabilize the grid. Self-consumption also found to be increased as much as 83% and 114% for a sunny and partly cloudy day, respectively. Duman and Guler¹⁶ integrated the PV technology with an optimized size of the battery system to produce electricity for off-grid LED road lighting systems in Turkey. Ghafoor and Munir¹⁷ designed and analyzed a stand-alone PV system for the electrification of a residential household. While modeling, the required PV power of 1,928 Wp and area of 12.85 m², battery backup storage capacity of 9,640.5 Wh, the inverter current of 56.65 A, and size of the charge controller 1,020 W were considered. That paper showed that the off-grid PV system is technically and economically appropriate technology for a single residential household in Pakistan. Off-grid systems such as bus shelters also employ the solar PV technology to overcome the problem of energy generation by non-renewable resources and to mitigate the environmental impacts.¹⁷ Solar PVs¹⁸ contribute to the reduction of CO₂ emissions and thus make a sustainable environment. Passive strategies along with renewable energy-generating resources help to make the net-zero building a success.¹⁹

The world is experiencing a shortage of freshwater, which is due to increased human activities.²⁰ Only 2.5% of the total water on earth is freshwater, out of which 70% is frozen, and 30% can be taken as moisture or underground aquifers.²¹ The atmospheric water generator can be an alternative to get the freshwater from the atmosphere in which the rate of the water produced depends on the relative humidity and ambient temperature.²² Different methods can be used to get freshwater from the atmosphere. Nerlekar²³ discussed the most prevalent method of refrigeration cycle dehumidification for generating the freshwater from the atmospheric humidity. Cooling coils in the refrigeration unit brings the circulated air around it below to its dew point, and water can be collected. Thermoelectric coolers are also available. It was found out that the system can produce 26 ml/h when relative humidity is 75% at temperature of 318 K after consuming only 20 W of power.²¹ In a study,²⁴ the authors employed air conditioner’s condenser as water source. They observed that for every 50°C rise in inlet air temperature,
the vapor condensation is increased by 0.5 kg/h. Daily average condensate data for the summer months of June, July, August, and September yield 34.5, 38.1, 70.1, and 59.4 kg of condensate water, respectively. The extraction of water by condensation process is affected by air humidity and temperature. Ibrahim et al.\textsuperscript{25} did the performance analysis of a solar cooling system. The simulation and parametric studies showed that 0.3 kg/s of collector fluid can give max efficiency and is able to produce 8 L/h at certain parameters such as $A_c = 28$ m$^2$, $T_f = 45^\circ C$, $I = 800$ W/m$^2$, and $R = 50\%$. The authors also conducted parametric study and recorded that the parameters such as solar flux, volume of fresh air, and relative humidity increase the efficiency of solar collector and COP of chiller, and it also effectively increases the rate of water production. Heidari et al.\textsuperscript{26} developed a solar-assisted desiccant-based evaporative cooling system, which provided coproduction of water and space cooling. Hourly simulation of 60-m$^2$ building showed that the moisture harvesting of exhausted regeneration air from evaporator yielded 590 L/week, which is sufficient for evaporator cooling water consumption, and it also produced an excess of 289 L for domestic usage. Other methods may include the Peltier effect,\textsuperscript{27,28} by using solar-based thermoelectric generator utilization.\textsuperscript{29}

Space cooling is extremely important in hot and arid climatic regions to provide the comfort to the occupants. A large part of energy is being consumed for the purpose to provide space cooling, and it adds the peak load to the grid.\textsuperscript{30} Different techniques have been studied and used to consume less electricity, and efforts have been done to use solar-driven cooling techniques to make the system more sustainable such as thermoelectric,\textsuperscript{31} hybrid solar PV-grid connected air conditioner,\textsuperscript{32} solar ejector,\textsuperscript{33} and desiccant solutions.\textsuperscript{34,35} Solar-assisted vapor compression/absorption cascaded air conditioning system shows a considerable saving in electricity consumption by the use of compression system.\textsuperscript{36} Patel et al.\textsuperscript{37} integrated Rankine cycle with cascaded vapor compression/absorption system to directly convert the heat into space cooling application without electricity, as cascaded refrigeration system has the advantage of conventional and stand-alone vapor absorption refrigeration system. The system demanded 19.15 kW and showed the energetic efficiency of 79.2\% for the overall system. The paper\textsuperscript{38} proposed solar energy-driven vapor compression refrigeration cycle for space cooling under real weather conditions. Simulation results showed that the system required a minimum solar radiation of 300 W/m$^2$ to operate the compression at its lowest speed, having COP of 1.85, and at 700 W/m$^2$, the speed of the compressor is at its maximum showing COP of 2.25. The review study\textsuperscript{39} evaluated 28 studies on cooling by water misting spraying systems to observe how efficiently and effectively the space can be cooled and also to show that it can easily be integrated to the already existing infrastructure. From the study, it was recorded that the wind speed, exposure time, and water injection density affect the performance of the spraying cooling system. The water misting spraying system for cooling works effectively if it has a high strength of approximately 3 MPa, to generate a droplet of 40 µm, and also if the ambient condition such as temperature is less than 30°C, relative humidity is more than 70\%.

From the conducted literature review, it has been concluded that the literature lacks in the annual assessment of an off-grid shelter that can show how much energy is produced, consumed by different components of the system; also, it lacks in providing space cooling and in generating freshwater (ie, from humid air) simultaneously through vapor compression cooling cycle. For solar energy–driven cooling system, most of the literature discusses only one technique for space cooling, either vapor compression refrigeration cycle or another technique, which can take up much of energy even though temperature is not too high. Combination of two space cooling techniques (vapor compression and misting), which can enable better control according to the ambient temperature, can save up energy when temperature is not too high.

This study thermodynamically analyzes the feasibility of an integrated system for an off-grid climate shelter. Batteries are attached to the system to support the nighttime and unfavorable solar irradiance conditions. The electricity generated by PV is used to supply power to the vapor compression cooling system/-atmospheric water generator, which provides the space cooling and freshwater for drinking and misting purposes by having the technique of refrigeration unit where water vapors are condensed to their dew point and the resulting water is collected. Here, the humid air is being harvested in conjunction with proper storage method and annual hourly assessment for a given location. The assessment is based on actual measurements and on the needs of a new shelter application. Considering the limitations of the shelter, the heat and power needs are optimized as well. A high-efficiency fan along with a water misting system is employed to give a cooling effect in the shelter when the vapor compression cooling system is not mandatory to operate. Engineering Equation Solver (EES)\textsuperscript{39} has been used to conduct the analyses of the off-grid climatic shelter.

The specific objectives of this study are listed as follows:

- To design an off-grid climatic shelter system by using semi-transparent photovoltaic cells.
- To analyze the designed system energetically and exergetically.
- To assess the energy and exergy efficiencies of each component in the system.
• To analyze the hourly energy production and consumption for a complete year.
• To harvest humid air in conjunction with proper storage method and annual hourly assessment for a given location. Considering the limitations of the shelter, the heat and power needs are optimized as well.
• To provide both space cooling and freshwater production by vapor compression cooling cycle.
• To assess the off-grid shelter for a complete year, the assessment is based on actual measurements and on the needs of a new shelter application.
• To study the effects of important operating parameters on the performance of the system.

2 | SYSTEM DESCRIPTION

This off-grid system is designed to get the energy from solar photovoltaic cells (main power source to meet the load requirements) and then to provide it to the climatic shelter to produce space cooling and to generate freshwater. Sunlight and humid air are the main inputs, whereas electrical energy, space cooling, and freshwater are the useful outputs of the system. The proposed off-grid sustainable climatic refuge system is shown in Figure 1. The size of the shelter considered is (4 m x 10 m x 2.8 m), this closed spaced climate shelter occupies a land area of 40 m². Since the shelter can be applied on the way to bus/tram stops, the capacities are considered accordingly. Bus/tram is scheduled to have a trip after every 20 min. On an average, the shelter occupancy has been taken as 15 persons per hour. The system is designed for peak consumption conditions in a hot summer day; therefore, it is expected to have extra energy generation in winter days.

The overall system can be divided into solar PV and energy storage systems, space cooling system, and atmospheric water generator (compressor, condenser, expansion valve, and evaporator), water pumping system, and fan.

2.1 | Solar PV and energy storage system

Solar PV generates electricity by absorbing the photons and converting it into electrical energy (electrons). Here, semi-transparent PV with an efficiency of 16.87% is considered. Semi-transparent PVs are mounted on the roof to allow some light into the shelter. To provide electricity supply in the evening and in bad weather conditions, the energy storage system is attached, which has a total energy capacity of 19.6 kWh at 298 K. When the surplus energy is produced in the daytime, it charges the battery and operates the system as well. The electricity generated from PVs enters the inverter—an inverter is selected to allow the peak energy to convert from DC to AC and to be used by the systems.

2.2 | Space cooling system and atmospheric water generator

A compressor is one of the four main components of the space cooling system and atmospheric water generator (AWG) (others are condenser, expander, and the evaporator). It circulates the refrigerant (R134a) through the compressor and increases pressure. The condenser cools down and condenses the vapors into liquid by increasing the pressure and rejecting the heat. Next, it passes through the expansion valve, which drops the pressure of the fluid and results in a temperature drop as well. Finally, the low-temperature refrigerant enters the evaporator, which also takes the ambient humid air. The evaporator vaporizes the refrigerant as it absorbs the heat from the inflowing humid air and cools down the humid air’s temperature to its dew point, causing the vapors to condense, and water can be collected in the water storage tank. The air passing through the evaporator has lower temperature than ambient temperature and is used for spacing cooling. The rate of water production in this system depends on relative humidity and ambient temperature. The rate increases as relative humidity and temperature increase. Atmospheric water generator does not work efficiently when the temperature falls below 291.45 K, or relative humidity drops below 30%. As the system is designed for peak consumption conditions in a hot summer day, it is expected that 15 L/day will be used for drinking purposes.

2.3 | Water pumping system and fan

Fan and water misting system are operational when the temperature is greater than 296.15 K but less than 301.15 K. This range of temperature is selected to consider the positive effect of water misting system for space cooling. For the temperature more than 301.15 K, the vapor compression cooling system operates for space cooling.

Water in the storage tank is used for the misting system to get the cooling effect in the shelter along with the fan. It consists of a pump, which picks up water from low pressure (of 101.3 kPa) and raises its pressure to the high-level pressure of approx. 1.000 kPa. With the high-level pressure, it is misted through the nozzle (filtration of 5 microns) to get the cooling effect inside the shelters. One nozzle consumes 0.00063 L/s and for each trip, 5 nozzles will be spraying water for 1 min to cover 10-m-long shelter. The fan creates a kinetic energy difference and causes the air flow. The incoming air enters has a velocity of ~0 m/s, and the exit velocity of air becomes about 15 m/s.
3 | SYSTEM ANALYSIS

The proposed system is assessed by energy and exergy analysis. The following assumptions are invoked during the analysis:

- The system operates at a steady state and steady flow.
- The reference environmental state has a temperature $T_0 = 298$ K and a pressure $P_0 = 101.3$ kPa.
- The changes in kinetic (except for the fan) and potential energy and exergy terms are negligible.
- The pressure losses in different components of the system are neglected.
- For battery, round trip efficiency of 95% is considered and the charging and discharging efficiencies are considered by the following equations:

$$
\eta_{\text{charging}} \cdot W_{\text{out}, PV} = W_{\text{PV},\text{storing}}
$$

$$
\eta_{\text{discharging}} \cdot W_{\text{PV},\text{storing}} = W_{\text{PV},\text{discharging}}
$$

where $\eta_{\text{charging}}$ is the charging efficiency, $W_{\text{out}, PV}$ is the work output by the solar PVs, $W_{\text{PV},\text{storing}}$ is the power stored in the battery, $\eta_{\text{discharging}}$ is the discharging efficiency, and $W_{\text{PV},\text{discharging}}$ is the discharged power from the battery storage system.

- Saturated liquid condition of refrigerant is considered at state point 7, and saturated vapor condition is considered at state point 5.

To analyze the overall system annually with more realistic manner, it is necessary to know the actual condition of the location. In this case, the city of Doha, Qatar, is being considered for the initial designing parameters of the system, and Table 1 shows the initial values used. The average values of temperature, pressure, and solar irradiance have been taken according to Qatar’s weather conditions from Hamad Bin Khalifa University solar test facility. Heat transmitted into the shelter due to semi-transparent PV has been calculated by equation (3).

$$
Q_{\text{shelter}} = Q_{\text{radiation,GH}} + Q_{\text{conduction}} + Q_{\text{human}} - Q_{\text{plants}} \quad (3)
$$

where $Q_{\text{shelter}}$ is the total heat transmitted in the shelter, $Q_{\text{radiation,GH}}$ is the heat transmitted inside the shelter through semi-transparent PVs, $Q_{\text{conduction}}$ is the heat conducted through the walls of the shelter, $Q_{\text{human}}$ is the heat accumulating due to human occupancy, and $Q_{\text{plants}}$ is the amount of heat absorbed by plants.

The heat accumulated in the shelter by radiation, that is, through the glass and semi-transparent part of the PV, is calculated by equation (4) and is as follows:
Here, $Q_{\text{solar,power}}$ is the heat of solar radiations transmitted inside the shelter through semi-transparent PVs, $A_{\text{transparent}}$ is the transparent area of the semi-transparent PVs, Glass transmittance is the extend of glass permitting the radiation to get through, $A_{\text{cell}}$ is the total area of the cells on the semi-transparent PVs, and $PV_{\text{transmittance}}$ is the amount of heat transmitted through semi-transparent PVs.

The heat inside the shelter that is accumulated by the conduction of side walls is calculated by the following equation (5):

$$Q_{\text{conduction}} = A_{\text{conduction}} \frac{(T_0 - T_{\text{shelter}})}{R}$$

Here, $Q_{\text{conduction}}$ is the heat transmitted through conduction, $A_{\text{conduction}}$ is the area considered for heat conduction, which is taken as 10 m² by considering one side of the wall, $T_0$ is the ambient temperature, $T_{\text{shelter}}$ is the temperature of the shelter, and $R$ is the resistivity of heat conducted through glass.

The shelter has the average occupancy of 15 persons/h; thus, the heat accumulated by the occupancy is calculated by the following equation (6):

$$Q_{\text{human}} = Q_{\text{human,one}} \times p$$

where $Q_{\text{human}}$ is the heat accumulated in the shelter due to human occupancy, $Q_{\text{human,one}}$ is the heat released by a human being, that is, 0.105 kW, and $p$ is the average number of people in the shelter at one tram/bus trip.

$$Q_{\text{plants}} = Q_{\text{plants,one}} \times \text{Total}_{\text{plants}}$$

where $Q_{\text{plants}}$ is the total heat absorbed by the plants in the shelter, $Q_{\text{plants,one}}$ is the heat absorbed by one plant, that is, $5 \times 10^{-6}$ kW, and Total$_{\text{plants}}$ is the total number of plants to be used in the shelter.

When sunlight strikes on solar PVs, the photon energy is converted into electrical energy. The energy balance equation can be written as

$$Q_{\text{Radiation}_{\text{shelter}}} = W_{\text{out,PV}} + Q_{\text{PVloss}} = I \times A_{\text{roof}}$$

where $Q_{\text{Radiation}_{\text{shelter}}}$ is total power input in kW, $W_{\text{out,PV}}$ is the work output regarded as the electrical power output by PV, $Q_{\text{PVloss}}$ are thermal losses of PV, $I$ is the average solar irradiance in Qatar, and $A_{\text{roof}}$ is the total area of the shelter's roof.

The work output/power generated can be calculated by the electrical efficiency formula of the solar PV:

$$W_{\text{out,PV}} = \dot{Q}_{\text{solar}} \times \eta_{\text{ele,PV}}$$

where electrical efficiency of the solar PV ($\eta_{\text{ele,PV}}$) can be found by the following formula:

$$\eta_{\text{ele,PV}} = \eta_{\text{std}} + a_{\text{tempCoeff}} \frac{(T_{\text{cell}} - T_0)}{100}$$

Here, $\eta_{\text{std}}$ is the efficiency of solar PV at standard conditions (ie, $T_0 = 25^\circ$C and $I_{\text{DNI}} = 1,000$ kW/m²), $a_{\text{tempCoeff}}$ is the temperature coefficient, and $T_{\text{cell}}$ is the temperature of the cell.

**TABLE 1** Initial input parameters for the system

| Parameters                          | Values                              |
|------------------------------------|-------------------------------------|
| Ambient temperature                | 298 K                               |
| Ambient pressure                   | 101.3 kPa                           |
| Relative humidity                  | 0.5                                 |
| Average solar irradiance           | 0.560 kW/m²                         |
| Installed area of PVs              | 40 m²                               |
| Cell type                          | Semi-transparent solar photovoltaic cells |
| Thermal coefficient                | $-0.40\%/^\circ$C                    |
| Size of one PV module              | $1,325 \times 992 \times 35$ mm     |
| Total number of PV panels          | 24                                  |
| Power rating of each module        | 200 W                               |
| Heat transmitted into the shelter through semi-transparent PV | 4.883 kW |
where $Q_{\text{Radiation}_{\text{shelter}}}$ is the heat entering the shelter through the roof, $Q_{\text{non}-\text{cell}}$ is the heat accumulation in the shelter by transparent parts of the roof, $Q_{\text{cell}}$ is the heat entering the shelter by the semi-transparent parts of the PV, and $PV_{\text{transmission}}$ is the transparency of the PV, which allows 10% of the radiations to transmit.

$$Q_{\text{cell}} = I \cdot A_{\text{cell}}$$ (12)

where $I$ is the average solar irradiance in Qatar, and $A_{\text{cell}}$ is the total covered by semi-transparent PV on the shelter’s roof.

The heat accumulation in the shelter by the transparent parts of the roof can be given by:

$$Q_{\text{non}-\text{cell}} = I \cdot A_{\text{non}-\text{cell}}$$ (13)

where $I$ is the average solar irradiance in Qatar, and $A_{\text{non}-\text{cell}}$ is the total transparent area on the shelter’s roof.

Overall, the energy efficiency $\eta_{\text{en,PV}}$ and the exergy efficiency $\eta_{\text{ex,PV}}$ for the PV can be calculated by:

$$\eta_{\text{en,PV}} = \frac{W_{\text{out,PV}}}{Q_{\text{solar}}}$$ (14)

$$\eta_{\text{ex,PV}} = \frac{W_{\text{out,PV}}}{Q_{\text{solar}} \left(1 - \frac{T_0}{T_{\text{solar}}}\right)}$$ (15)

where $Q_{\text{solar}}$ is total power input from solar energy in kW, $W_{\text{out,PV}}$ is the work output regarded as the electrical power output from PV, and $T_0$ and $T_{\text{solar}}$ are the ambient and sun surface temperatures, respectively. For the whole system, the subsystem and component energy balance equations are formed by using the first law of thermodynamics, and for exergy analysis, the second law of thermodynamics is used.

For calculating the freshwater generation, the following equations have been used:

$$m_9 \cdot h_9 = m_{10} \cdot h_{10} + m_{11} \cdot h_{11} + \dot{Q}_{\text{avai}WG}$$ (16)

$$\dot{Q}_{\text{avai}WG} = \dot{Q}_{\text{evaporator}} \cdot (1 - r_{\text{cooling, evaporator}})$$ (17)

Here, $m_9$ is the mass flow rate of humid air entering the evaporator inlet, $m_{10}$ is mass flow rate of dry air exiting evaporator outlet, $m_{11}$ is the mass flow rate of freshwater generation, $h_9$, $h_{10}$, and $h_{11}$ are enthalpies for their mentioned respective state points, $Q_{\text{avai}WG}$ is the heat transfer rate of water generator, $\dot{Q}_{\text{evaporator}}$ is the heat transfer rate of evaporator, and $r_{\text{cooling, evaporator}}$ is percentage share of the cooling load in the evaporator. The cooling load is set to be 55% as it takes more power for space cooling.

The energetic and exergetic coefficient of performance (COP) for space cooling system/groundwater pump (AWG) is given as:

$$\text{COP}_{\text{en,AWG}} = \frac{m_5 \cdot h_5 - m_8 \cdot h_8}{W_{\text{compressor}}}$$ (18)

$$\text{COP}_{\text{ex,AWG}} = \frac{m_5 \cdot e_5 - m_8 \cdot e_8}{W_{\text{compressor}}}$$ (19)

The energy and exergy efficiency of the water pumping system is calculated by the following equations:

$$\eta_{\text{en,pump}} = \frac{m_{13} \cdot h_{13} - m_{12} \cdot h_{12}}{W_{\text{pump}}}$$ (20)

$$\eta_{\text{ex,pump}} = \frac{m_{13} \cdot e_{13} - m_{12} \cdot e_{12}}{W_{\text{pump}}}$$ (21)

Here, $\eta_{\text{en,pump}}$ and $\eta_{\text{ex,pump}}$ are the energy and exergy efficiencies of the water pump, respectively. $W_{\text{pump}}$ is the power required by the pump, $m$ is the mass flow rate (kg/s), $h$ is the enthalpy (kJ/kg), and $e$ is exergy (kJ/kg) for their respective state points mentioned with them.

The fundamental balance equations of system components are given in Table 2.

The energy and exergy efficiencies for the fan are as follows:

$$\eta_{\text{en,fan}} = \frac{m_{16} \cdot V_{\text{exit}}^2}{2000} + m_{16} \cdot h_{16} - m_{15} \cdot h_{15}$$ (22)

$$\eta_{\text{ex,fan}} = \frac{m_{16} \cdot V_{\text{exit}}^2}{2000} + m_{16} \cdot e_{16} - m_{15} \cdot e_{15}$$ (23)

where $m_{16}$ is the mass flow rate (kg/s) of air, $h$ is the enthalpy (kJ/kg), $V_{\text{exit}}$ is the air velocity exiting the fan, and $e$ is specific exergy (kJ/kg). $W_{\text{fan}}$ is the power required by the fan.
The overall energy and exergy efficiencies of the system are given as

$$\eta_{en, \text{overall}} = \frac{W_{\text{out,PV}} - W_{\text{compressor}} - W_{\text{fan}} - W_{\text{pump}} - W_{\text{light}} + Q_{\text{eva}} + m_{16} \frac{V_{\text{exit}}^2}{2000} + m_{13} \cdot h_{13}}{Q_{\text{solar}} + m_{15} \cdot h_{15} + m_9 \cdot h_9 + Q_{\text{shelter}}} \tag{24}$$

$$\eta_{ex, \text{overall}} = \frac{W_{\text{out,PV}} - W_{\text{compressor}} - W_{\text{fan}} - W_{\text{pump}} - W_{\text{light}} + Q_{\text{eva}} \left(1 - \frac{T_e}{T_{\text{avg}}} \right) + m_{16} \frac{V_{\text{exit}}^2}{2000} + m_{13} \cdot e_{13}}{Q_{\text{solar}} \cdot \left(1 - \frac{T_e}{T_{\text{avg}}} \right) + m_{15} \cdot e_{15} + m_9 \cdot e_9 + Q_{\text{shelter}} \cdot \left(1 - \frac{T_e}{T_{\text{avg}}} \right)} \tag{25}$$

where $W_{\text{out,PV}}$ is the power output from the solar PV, $V_{\text{exit}}$ is the velocity of the air flowing through the fan, $W_{\text{compressor}}$, $W_{\text{fan}}$, $W_{\text{pump}}$, and $W_{\text{light}}$ are the power required by compressor, fan, pump, and light, respectively. $Q_{\text{solar}}$ is the total energy input into PV cells, and $Q_{\text{eva}}$ is the amount of heat absorbed by the evaporator. $m$, $h$, and $e$ are the mass flow rate (kg/s), specific enthalpy (kJ/kg), and specific exergy (kJ/kg) corresponding to their subscripted state points.

### 4 | RESULTS AND DISCUSSION

The efficiencies and outputs are discussed in this section for the entire system. EES (Engineering Equation Solver) software$^{39}$ is used to define the state points and to calculate the thermodynamic properties of the entire system. The reference state points for working materials (water, humid air, and R134a—refrigerant) are taken as ambient temperature and pressure conditions, as shown in Table 1. The temperature (K), pressure (kPa), specific enthalpy (kJ/kg), specific entropy (kJ/kg), specific exergy (kJ/kg), and mass flow rate (kg/s) are calculated as shown in Table 3.

The input parameters such as ambient temperature and pressure, relative humidity, solar PVs used, PVs’ installed area and efficiency, irradiance, and heat accumulated in the shelter due to transmittance of semi-transparent PVs are shown in Table 1. Energy and exergy analyses have been performed based on these ambient parameters and considering the state points.

The overall energy and exergy efficiencies of the considered system are 19.45% and 9.584%, respectively. The solar PV produces 4.479 kW of power in total, out of which 1.903 kW is taken by the compressor, 1.339 kW is needed by the fan to operate.

Table 4 shows the exergy destruction rates for the major components of the system. It can be seen clearly that solar PV has the greatest exergy destruction ratio of 92% in all the system components. Due to low conversion efficiency from solar to electricity and exposure to high solar irradiance input, solar PV exhibits higher exergy destruction rate.

Table 5 shows the exergy efficiencies of solar PVs, fan, pump, overall system, and also exergetic COP of cooling/water generating system. The exergy efficiency of the PV shows its ability to convert the incident solar irradiance into useful work, and the exergy efficiency of fan computes its effectiveness for the system. COP$_{ex}$ of vapor compression cooling system is an indicator of the actual performance of the cooling system. Table 5 shows a lower value of COP$_{ex}$ as exergy destruction rates of compressor, condenser and evaporator are considered in the system.

### 4.1 | Hourly analysis

#### 4.1.1 | Winter day

Weather data for a randomly chosen winter day (January 12, 2017) in Qatar in 2017 are shown in Table 6. It gives hourly weather report of temperature (K), solar irradiance (kW/m$^2$), relative humidity (%), and wind speed (m/s). This particular year (2017) is chosen because of the wind data availability for the region.

Figure 2(A) shows the hourly power generation, consumption, storage, and shortage in the shelter. Solar energy is the main and only source for this off-grid system to produce electricity, so the energy is produced during the daytime only. The maximum power generated on this day is 4.88 kW when the solar irradiance is 0.61 kW/m$^2$; it can be calculated by equation (9). The total power production and consumption are 31.69 kW and 11.64 kW, respectively, for this day. Excessive energy is stored in the battery to keep the system operational in bad weather conditions as well. The energy generated is either used by AWG for the freshwater generation (3–4 h) or light (15–17 h) when the solar irradiance is lower than 0.2 kW/m$^2$. AWG is functional when relative humidity is high, which is mostly at nighttime. Figure 2(A) shows the energy shortage when AWG or light is operational because the system cannot generate any electricity at nighttime. Therefore, AWG and light get the stored energy from the battery to function accordingly. The selected day is from the winter season;


Table 2: Mass-, energy-, entropy-, and exergy-balance equations of different components

| Components | Energy balance | Entropy balance | Exergy balance |
|------------|----------------|----------------|----------------|
| Solar PV   | $Q_{in} = 0$ | $m_{solar} h_{s} = m_{out, PV} h_{out, PV}$ | $m_{solar} s_{s} = m_{out, PV} s_{out, PV}$ |
| Compressor | $m_{h} h_{h} = m_{out, comp} h_{out, comp}$ | $m_{h} s_{h} = m_{out, comp} s_{out, comp}$ | $m_{h} s_{h} = m_{out, comp} s_{out, comp}$ |
| Condenser  | $m_{h} h_{h} = m_{out, cond} h_{out, cond}$ | $m_{h} s_{h} = m_{out, cond} s_{out, cond}$ | $m_{h} s_{h} = m_{out, cond} s_{out, cond}$ |
| Expansion valve | $m_{h} h_{h} = m_{out, exp} h_{out, exp}$ | $m_{h} s_{h} = m_{out, exp} s_{out, exp}$ | $m_{h} s_{h} = m_{out, exp} s_{out, exp}$ |
| Evaporator | $m_{h} h_{h} = m_{out, evap} h_{out, evap}$ | $m_{h} s_{h} = m_{out, evap} s_{out, evap}$ | $m_{h} s_{h} = m_{out, evap} s_{out, evap}$ |
| Fan        | $m_{h} h_{h} = m_{out, fan} h_{out, fan}$ | $m_{h} s_{h} = m_{out, fan} s_{out, fan}$ | $m_{h} s_{h} = m_{out, fan} s_{out, fan}$ |
| Pump       | $m_{h} h_{h} = m_{out, pump} h_{out, pump}$ | $m_{h} s_{h} = m_{out, pump} s_{out, pump}$ | $m_{h} s_{h} = m_{out, pump} s_{out, pump}$ |

Therefore, there is no need for space cooling as the temperature is low.

Figure 2(B) shows the hourly freshwater generation by AWG in a winter day; it is calculated by the equation (16). The freshwater generated in winters is used only for drinking purposes, as no water is needed by the misting system for cooling purposes. The requirement for drinking water becomes less in winter season; thus, if AWG is operational for 3–4 h, it will be able to generate 10–15 L/day.

4.1.2 | Summer day

Another day selected for analysis is from a hot and humid summer of Qatar. The hourly weather data for a random summer day (July 12, 2017) are given in Table 7. It helps in calculating the energy production by solar PVs as shown in energy balance equation of solar PV in Table 2. It also helps in determining which cooling system (vapor compression cooling system or fan and water misting system) should be operational based on temperature. Relative humidity is an indicator of how much freshwater can be collected by AWG.

The total energy produced and consumed for the whole day is 43.24 kWh and 36.21 kWh, respectively. Air conditioner (AC) is operational for the daytime when the temperature is more than 301.15 K consuming 1.91 kW; otherwise, fan and water misting system is working together consuming 1.34 kW of power. Furthermore, AWG is operational at nighttime (for 3–4 h) as the relative humidity of air is higher at that time (consuming power of 1.91 kW), and it is easier to collect more water from the atmosphere in less time. Also, light works (power rate of 0.014 kW) at nighttime for 14–15 h. The energy generated during daytime is supplying electricity to AC at the same time. The battery storage system is saving the excessive energy to keep the system operational in the evening and nighttime as shown in Figure 3(A).

Hourly production of freshwater by AWG can be seen in Figure 3(B). It is shown that freshwater generated is used for drinking and water misting purposes. The requirement for drinking water in summer is around 15 L, and for water misting cooling purposes, water needed is about 10 L. It can be seen in Figure 3(B) that the water generation increases as the relative humidity increases and temperature decreases. Thus, it is better to keep the AWG operational at nighttime as the humidity is higher and temperature is lower after 19:00. More water can be collected in the evening in less time. To fulfill the requirements, AWG must be operational for 4–6 h.
4.2 | Energy distribution

To observe the energy distribution between different components in the shelter, a random day (29/07/2017) has been selected in Qatar. 53.97 kWh of energy can be produced by semi-transparent PVs; the energy consumption at daytime by space cooling systems altogether is 15.98 kWh. About 38 kWh of excess of energy produced at daytime will charge the battery to keep the system operational at nighttime. 16.98 kWh power will be used for lighting, air-to-water generator, and space cooling purposes at nighttime.

4.3 | Monthly analysis

This section discusses hourly electricity production (by Solar PV), its consumption (AC, AWG, light, fan, and pump), energy storage, and shortage for each month considering solar irradiance, temperature, relative humidity, and considering the public holidays and short working days.

In Figure 5(A,B), the maximum energy produced is 5.77 kW and 7.12 kW when the solar irradiance is 0.72 and 0.89 kW/m² in January and February, respectively. January and February are winter months in Qatar, that is why the off-grid shelter is not using AC and fan any time. The energy produced is either used by AWG for a freshwater generation or light when the solar irradiance is lower than 0.2 kW/m² and the rest of the produced energy is stored in the battery for bad weather conditions or when there is no solar energy available. AWG is functional when relative humidity is high, which is mostly at nighttime. In Figure 5(B), it is shown that there is energy shortage when the AWG is operational because the system is currently not generating any electricity at nighttime. It

| State points | T (K) | P (kPa) | h (kJ/kg) | s (kJ/kg. K) | ex (kJ/kg) | m (kg/s) |
|--------------|-------|---------|-----------|--------------|------------|----------|
| 0            | 298   | 101.3   | 104.3     | 0.3651       | –          | –        |
| 1            | 298   | 101.3   | 49.9      | 5.787        | 0          | –        |
| 2            | 298   | 101.3   | 49.9      | 5.787        | 0          | –        |
| 3            | 298   | 101.3   | 49.9      | 5.787        | 0          | –        |
| 4            | 298   | 101.3   | 49.9      | 5.787        | 0          | –        |
| 5            | 268   | 200     | 248.7     | 0.9536       | 17.41      | 0.047    |
| 6            | 330.4 | 1000    | 289.1     | 0.9722       | 52.34      | 0.047    |
| 7            | 307.3 | 1000    | 99.62     | 0.367        | 43.16      | 0.047    |
| 8            | 268   | 200     | 99.62     | 0.3872       | 37.16      | 0.047    |
| 9            | 298   | 101.3   | 49.9      | 5.787        | 0          | 0.1666   |
| 10           | 293   | 101.3   | 30.84     | 5.72         | 0.8559     | 0.1657   |
| 11           | 293   | 101.3   | 56.88     | 5.811        | −0.2498    | 0.0009069|
| 12           | 298   | 101.3   | 104.3     | 0.3651       | 0          | 0.0003628|
| 13           | 298.1 | 1000    | 105.4     | 0.3656       | 0.9012     | 0.0003628|
| 15           | 295   | 101.3   | 42.65     | 5.762        | 0.199      | 0.1657   |
| 16           | 297   | 107.3   | 50.58     | 5.772        | 4.944      | 0.1657   |

| System components | PV | Compressor | Condenser | Evaporator | Fan |
|-------------------|----|------------|-----------|------------|-----|
| Exergy destruction rates (kW) | 16.77 | 0.2606 | 0.2947 | 0.1438 | 0.5264 |

| System components | PV | Fan | Pump | Cooling/water generating system (COP<sub>ex</sub>) | Overall system |
|-------------------|----|-----|------|-----------------------------------------------|---------------|
| Exergy efficiency (%) | 21.08 | 60.69 | 85 | 0.488 | 9.58 |
gets the excess stored energy from the battery accordingly. In March, the maximum power produced by solar PVs is 7.53 kW as shown in Figure 5(C). As the temperature starts to increase in this month, for the comfort of pedestrians, fan and water misting are operated at daytime when the temperature exceeds 296.15 K. Furthermore, AWG is working at nighttime but now for longer hours as the off-grid shelter needs water for the water misting system in addition to drinking. It starts getting hotter in April, as can be seen in Figure 4(D); AC starts to work when the temperature exceeds 301.15 K. From May to September, it is summer season in Qatar and off-grid shelter demands for high energy consumption as AC is working mostly from 10:00 am to 5:00 pm. In evening, the fan along with water misting system operate to keep the comfort of the pedestrians. It can be seen in Figure 5(E–I) that AWG is operational at night because of the higher relative humidity level of air to fulfil the needs. The solar PV system generates enough electricity to keep the cooling system working and storing the excess of energy for nighttime. From October to December, as the weather starts to get better, it can be seen in Figure 5(J–L) that the energy generation is more than consumption and more energy is saved. The cooling system (either AC or fan) works until the mid of November.

### 4.4 | Sensitivity analysis

A sensitivity analysis has been performed by varying input parameter values and recording the corresponding results on different outputs as discussed below.

#### 4.4.1 | Effect of varying cell temperature

Ambient temperature and cell temperature are important parameters in studying the thermodynamic properties of the system. The temperature of the PV panels is quite...
significant for the performance. As the ambient temperature rises, it causes the cell temperature to rise as well. The relation between ambient temperature and cell temperatures is given, and cell temperature $T_c$ is calculated based on the following correlation:

$$T_c = T_o + I_{rPOA} \cdot e^{(-3.473 - 0.0594v)}$$  \hspace{1cm} (26)

Here, $v$ is wind speed, $T_o$ is ambient temperature, and $I_{rPOA}$ is the irradiance (plane of array) on solar PV.

Figure 6(A) shows that varying the cell temperature affects the energy and exergy efficiencies of the solar PV. The selected cell temperature is from 290 K to 315 K, which is by the ambient temperature and keeps on decreasing the energy and exergy efficiencies of the solar PV from 22.2 to 15% and 23.4 to 16%, respectively.

Figure 6(B) shows that increasing cell temperature decreases the overall energy and exergy efficiency of the system. The ambient temperature causes the cell temperature to rise, which as well affects the performance of each component in the system and results in decreasing the energy and exergy efficiencies of the system.

Electricity produced by solar PVs is also affected by an increase in cell temperature. Ambient temperature causes the cell temperature to increase; thus, more energy will be lost as $Q_{\text{loss, PV}}$, and less useful work is done by PVs $W_{PV}$ as can be shown in equation (8). Less electricity production through PV causes a decrease in the production of a surplus amount of electricity, which does not allow the battery to store sufficient charge, and thus, the charge availability decreases over as the cell temperature increases (Figure 6(C)). It is important to note that due to active cooling available in the shelter, the PV surface temperatures can be kept at lower levels, helping to increase the efficiency.

4.4.2 | Effects of irradiance

As the value of irradiance depends on the location and time, it is important to observe the parametric changes that can be seen while varying the irradiance. In Figure 6(A), varying the value of irradiance, from 0.5 to 1.0 kW/m$^2$,
which is the average minimum and maximum irradiance for Qatar, affects the exergy efficiency and exergy destruction of PV. As can be seen in equation (15), the relation of the exergy efficiency of PV is inversely proportional to $Q_{solar}$, which is the product of irradiance, and area in equation (8) causes the exergy efficiency to slightly decrease as it has a small value of the thermal coefficient. However, there is a significant increase in the exergy destruction rate of PV due to an increase in useful work output by PVs with an increase in irradiance value.

Figure 7(B) shows that the charge availability depends on the variation in solar irradiance as well. Solar PV system generates more electricity as the value of solar irradiance increases. Thus, providing a surplus amount of electricity will allow the battery to store more charge and charge availability gets more and more as the solar irradiance value keeps on increasing. Heat accumulation inside the climate shelter increases as the solar irradiance value increases. It is due to the increase in ambient temperature, and thus, this heat is conducted to the shelter resulting in increasing the heat accumulation in the shelter.

### 4.4.3 Effect of relative humidity

Relativity humidity of the air also depends on the location and time of the day and year as well. Figure 8(A) shows the production of freshwater, which depends on the relative humidity of the selected location. As relative humidity increases, the freshwater production from AWG increases, which as well is used for drinking and water misting purposes in the shelter.

Electricity, space cooling, and freshwater production are the main outputs of the system. So, the energy and exergy efficiencies of the system depend on the relative humidity of the air along with the other parameters. Increasing ambient relative humidity significantly increases the overall energy and exergy efficiencies of the entire system as shown in Figure 8(B).

### 4.4.4 Effect of the area of PV

This parametric study in Figure 9(A) shows the effect of increasing the area for installed solar PV on electricity
production from the PV system. The PV area is a limitation since the rooftop has a certain capacity. As the installed area for PV increases, it starts increasing the electricity production by the PV system and battery storage starts storing more energy for nighttime use or in bad weather condition use. This shows that increasing the area can aid to provide comfort for a longer time as more electricity will be generated, and more charging will be available for the time when no solar energy is available. Below certain PV area, there is not enough electricity to be stored in the batteries. Therefore, it is important to maximize the effective use of the area.

Moreover, increasing the area of the shelter means that more heat will be conducted through solar radiation to the shelter, and thus, heat accumulation in the shelter will also increase with this parameter as in Figure 9(B).

4.4.5 | Effects of other significant parameters

Ambient temperature is one of the parameters that is the place- and time-dependent. Figure 10(A) shows the relation between ambient temperature on the energetic and exergetic coefficient of performance COP of the cooling system and AWG. As the ambient temperature increases, it does not change the energetic COP; however, the exergetic COP of the cooling system increases with the increase in ambient temperature. It is mainly because of the high-temperature difference between the condenser outlet and ambient temperature.

The working fluid (in this case is R134a) in the vapor compression cooling system circulates and absorbs the heat from the space and lowers the temperature. This absorbed heat is rejected through the condenser. It can be observed that if the mass flow rate is increased, more energy is required by the compressor to provide space cooling and more energy is needed for AWG. Furthermore, the increase in the mass flow rate of R134a from 0.03 to 0.08 kg/s will significantly lower the overall exergy efficiency of the system from 13.6 to 1.5% as shown in Figure 10(B).

Semi-transparent PV has been selected for this designed system, which transmits only a portion of the light to the system. As the transmission value of PV increases.
from 0 to 1, the heat starts accumulating in the system also increases from 5 to 21 kW. Also, the overall energy efficiency of the system starts decreasing as the PV transmittance value increases and can be seen in Figure 10(C).

Figure 10(D) shows a parametric study that records the effect of cooling load on space cooling and energy required by AWG for a freshwater generation. As the cooling load increases in the shelter because of solar conduction through walls and radiation through semi-transparent PVs as well as people’s occupancy, the energy required for space cooling increases as well. Increasing cooling load pulls the energy more toward the space cooling rather than the water fresh production. Thus, when the cooling load increases, the energy required for the space cooling increases, and the energy provided to the AWG decreases.

A human body keeps on releasing the heat to keep their body temperatures maintained. This parametric study investigates the effect of increasing the total people in the shelter on heat accumulation. As the people are increasing, the heat accumulation value is also rising which means that the system will need more energy for space cooling, and this will decrease the overall energy efficiency of the system as can be seen in Figure 10(E).

4.5 | Environmental impact

To compare the environmental effect of the off-grid shelter driven by solar energy to the one grid connected, it can be seen in Table 8 that the same shelter if provided with grid electricity for all requirements, 80% of the electricity (6.08 MWh) is originated from the natural gas and 20% (1.519 MWh) of the electricity is originated from diesel combustion. Table 8 compares the CO₂ emissions generated by getting the required energy from the grid to the designed shelter (excluding the manufacturing of the material and electrical devices used in the shelter) with the proposed off-grid method; about 1,480 kg CO₂ is saved annually.

5 | CONCLUSION

In this study, energy and exergy analyses for the full solar-based off-grid system for a climate refuge are performed comprehensively. Storage batteries are attached to keep the system running at nighttime and in unfavorable solar energy conditions. Promising results have been achieved to produce electricity and can be used by a vapor compression cooling system (to provide space cooling and
to produce freshwater), fan, water pumping system, and light (for nighttime only). The main findings of the study are listed as follows:

- AWG is able to produce 3.265 L/h of water at 298 K of ambient temperature with 50% of relative humidity in the air. In winters, water in the shelter is only needed for drinking purposes after filtering; hence, AWG will be operational for only 3–4 h/day, whereas in summers, water is needed not only for drinking but also for water misting purpose as well; hence, AWG will be able to generate the required amount of water (about 25 L) in 5–6 hours/day.
- In one typical summer day, the energy produced by the semi-transparent solar PV is 43.24 kWh and the consumption is about 36.21 kWh by the shelter, and in one summer month (ie, July), the energy production is 1,589.09 kWh and the consumption is about 1,016.10 kWh mainly for space cooling and freshwater generation purposes.
FIGURE 6  (A) Effects of cell temperature on energy and exergy efficiency of solar PV, (B) on the overall energy and exergy efficiency of the system, and (C) on electricity produced by PVs and charge availability in the battery.

FIGURE 7  (A) Effects of solar irradiance on exergy efficiency and exergy destruction of PV, (B) on battery charging availability and heat accumulated in the shelter.
For one typical winter day, the amount of energy produced by semi-transparent solar PV is 31.69 kWh, and the consumed energy by the shelter is 11.64 kWh. The energy production for a winter month (January) is about 919.80 kWh while the consumption is about 233.69 kWh only for freshwater generation and lighting purposes.

The parametric study shows the ability of the system to be operated at different locations having different irradiance, ambient temperature, solar cell temperature, shelter temperature, relative humidity, area of installed PV, semi-transparent PV transmittance, the mass flow rate of R134a, load demand, and occupancy in the shelter. Higher values of irradiance show higher power output by PV along with higher exergy destruction rates. Ambient temperature affects the exergetic COP of the cooling system inversely, an increase in cell temperature decreases the power output of the solar PVs; also, the overall efficiency of the system is decreased.

For one typical winter day, the amount of energy produced by semi-transparent solar PV is 31.69 kWh, and the consumed energy by the shelter is 11.64 kWh. The energy production for a winter month (January) is about 919.80 kWh while the consumption is about 233.69 kWh only for freshwater generation and lighting purposes.

The parametric study shows the ability of the system to be operated at different locations having different irradiance, ambient temperature, solar cell temperature, shelter temperature, relative humidity, area of installed PV, semi-transparent PV transmittance, the mass flow rate of R134a, load demand, and occupancy in the shelter. Higher values of irradiance show higher power output by PV along with higher exergy destruction rates. Ambient temperature affects the exergetic COP of the cooling system inversely, an increase in cell temperature decreases the power output of the solar PVs; also, the overall efficiency of the system is decreased.

Furthermore, the increase in relative humidity increases the freshwater generation in addition to increasing the overall system efficiency.

- The energy and exergy efficiencies of the overall system are 19.45% and 9.58%, respectively.
- The exergetic COP of atmospheric water generator and cooling system is calculated as 0.4878.

The system can be easily rescaled and can be applied to a different location accordingly to the load demands. For future studies, different types of solar PVs can be considered to study the overall efficiency of the system. Also, the system can be redesigned according to the location and energy demands of where it is going to be deployed. Different methods of space cooling and freshwater generation can be a part of future studies. The multi-objective optimization of the system can also be considered for future studies.
FIGURE 10  (A) Effect of ambient temperature on energy and exergy COP of AWG. (B) Effect of the mass flow rate of R134a on the energy required by the compressor and overall exergy efficiency of the system. (C) Effect of PV transmittance on heat accumulation in the shelter and overall energy efficiency of the system. (D) Effect of cooling load on space cooling and energy required for AWG. (E) Effect of occupancy in the shelter on heat accumulated in the shelter and overall energy efficiency of the system.
NIAZ AND BICER

ACKNOWLEDGMENTS
The authors acknowledge the support provided by the Hamad Bin Khalifa University, Qatar Foundation, Qatar (210023019). Open access funding is provided by Qatar National Library (QNL).

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| $A$    | Area (m²)   |
| $h$    | Specific enthalpy (kJ/kg) |
| $P$    | Pressure (kPa) |
| $Q$    | Heat transfer rate (kW) |
| $s$    | Specific entropy (kJ/kg) |
| $T$    | Temperature (K) |
| $V$    | Velocity (m/s) |
| $\dot{W}$ | Work rate (kW) |

Acronyms

| Acronym | Description |
|---------|-------------|
| AWG     | Atmospheric water generator |
| COP     | Coefficient of performance |
| EES     | Engineering Equation Solver |
| En      | Energy |
| Ex      | Exergy |
| PV      | Photovoltaic |

Subscripts

| Subscript | Description |
|-----------|-------------|
| $c$       | Cell |
| Elec      | Electrical |
| en        | Energy |
| ex        | Exergy |
| temp. coff. | Temperature coefficient |
| std       | Standard |
| $v$       | Wind speed (m/s) |

Greek letter

| Greek letter | Description |
|--------------|-------------|
| $\eta$       | Efficiency |

ORCID

Fariha Niaz @ https://orcid.org/0000-0002-4342-0967
Yusuf Bicer @ https://orcid.org/0000-0003-4753-7764

REFERENCES

1. Irfan M, Abas N, Saleem MS. Thermal performance analysis of net zero energy home for sub zero temperature areas. *Case Stud Therm Eng.* 2018;12:789-796. doi:10.1016/j.csite.2018.10.008
2. Tamang R, Ghatani S. Sustainable Humanosphere 486 Climate Change and its Adverse effects: A Concern of Human Kind, 2020.
3. Govinda Rao P, Al-Kuwari MMSA. Assessment of Solar and Wind energy potential in Qatar. 2013.
4. Sun J, Jasieniak JJ. Semi-transparent solar cells. *J Phys D Appl Phys.* 2017;50:doi:10.1088/1361-6463/aa53d7
5. Miyazaki T, Akisawa A, Kashiwagi T. Energy savings of office buildings by the use of semi-transparent solar cells for windows. *Renew Energy.* 2005;30:281-304. doi:10.1016/j.renene.2004.05.010
6. Shukla AK, Sudhakar K, Baredar P. Exergetic analysis of building integrated semitransparent photovoltaic module in clear sky condition at Bhopal India, *Case Stud. Therm Eng.* 2016;8:142-151. doi:10.1016/j.csite.2016.06.009
7. Alsema EA, Goud JM & Kuil JW Challenges for building integrated PV in high-rise urban environments - the example of PV on utrecht central station, In: 2009:4235 - 4240. doi:10.4229/24thEUPVSEC2009-5BV.2.64
8. Frontini SF, Bonomo P, Chatzipanagi A, Verberne G, van den Donker M & Folkerts W. BIPV product overview for solar façades and roofs. 2015.
9. Olsson KATEA. How to supply bus stops with electricity without connecting them to the electricity grid. 2013.
10. Khatib T, Mohamed A, Sopian K. A review of photovoltaic systems optimization techniques. *Renew Sustain Energy Rev.* 2013;22:454-465. doi:10.1016/j.rser.2013.02.023
11. Ren Z, Paevere P, Chen D. Feasibility of off-grid housing under current and future climates. *Appl Energy.* 2019;241:196-211. doi:10.1016/j.apenergy.2019.03.068
12. Tsiaras E, Papadopoulos DN, Antonopoulos CN, Papadakis VG, Coutelieris FA. Planning and assessment of an off-grid power supply system for small settlements. *Renew Energy.* 2020;149:171-181. doi:10.1016/j.renene.2019.10.118
13. Ishaq M, Ibrahim UH, Abubakar H. Design of an off grid photovoltaic system: a case study of Government Technical College, Wudil, Kano State. *Int J Sci Technol Res.* 2013;2:175-181.
14. Hassan Q. Evaluation and optimization of off-grid and on-grid photovoltaic power system for typical household electrification. *Renew Energy.* 2021;164:375-390.
15. Jaszczur M, Hassan Q. An optimisation and sizing of photovoltaic system with supercapacitor for improving self-consumption. *Appl Energy.* 2020;279:115776.
16. Duman AC, Güler Ö. Techno-economic analysis of off-grid photovoltaic LED road lighting systems: a case study for northern, central and southern regions of Turkey. *Build Environ.* 2019;156:89-98. doi:10.1016/j.buildenv.2019.04.005

### Table 8 Grid connected vs off-grid climatic shelter CO₂ emission during operation

| Energy source                          | Annual energy requirement (kWh) | CO₂ emission (kg CO₂/kWh) | Annual CO₂ emission (kg CO₂/year) |
|----------------------------------------|---------------------------------|---------------------------|-----------------------------------|
| Grid electricity in the shelter        |                                 |                           |                                   |
| Natural gas                            | 6,078.053 (80%)                 | 0.181                     | 1,100.128                         |
| Diesel                                 | 1,519.51 (20%)                  | 0.250                     | 379.88                            |
| Proposed off-grid solar-based shelter |                                 |                           |                                   |
| Solar PVs                              | 7,597.563                       | 0                         | 0                                 |

TABLE 8 Grid connected vs off-grid climatic shelter CO₂ emission during operation
17. Ghafoor A, Munir A. Design and economics analysis of an off-grid PV system for household electrification. *Renew Sustain Energy Rev.* 2015;42:496-502. doi:10.1016/j.rser.2014.10.012

18. Khamisani AA. Design Methodology of Off-Grid PV Solar Powered System (A Case Study of Solar Powered Bus Shelter). 2018.

19. Dabaieh M. Minus carbon and plus energy refugee shelter. In: Jankovic L, ed. *Zero Carbon Buildings Today and in the Future.* Birmingham: University of Birmingham; 2016:71-76.

20. Mekonnen MM, Hoekstra AY. Four billion people facing severe water scarcity. *Am Assoc Adv Sci.* 2016;2.

21. Elsami M, Tajeddini F, Etaati N. Thermal analysis and optimization of a system for water harvesting from humid air using thermoelectric coolers. *Energy Convers Manag.* 2018;174:417-429. doi:10.1016/j.enconman.2018.08.045

22. Tripathi A, Tushar S, Pal S, Lodh S, Tiwari S, Desai RS. Atmospheric water generator. *Int J Enhanc Res Sci Technol Eng.* 2016;5:69-74.

23. Nerlekar SP. Atmospheric water generator: air drops. *Int J Adv Res Trends Eng Technol.* 2017;4:8-12.

24. Al-Farayedhi AA, Ibrahim NI, Gandhidasan P. Condensate as a water source from vapor compression systems in hot and humid regions. *Desalination.* 2014;349:60-67. doi:10.1016/j.desal.2014.05.002

25. Ibrahim NI, Al-Sulaiman FA, Saidur R. Performance assessment of water production from solar cooling system in humid climate. *Energy Convers Manag.* 2016;127:647-655. doi:10.1016/j.enconman.2016.09.056

26. Heidari A, Roshandel R, Vakiloroaya V. An innovative solar assisted desiccant-based evaporative cooling system for co-production of water and cooling in hot and humid climates. *Energy Convers Manag.* 2019;185:396-409. doi:10.1016/j.enconman.2019.02.015

27. Nandy A, Saha S, Ganguly S, Chattopadhyay S. A project on atmospheric water generator with the concept of Peltier effect. *Int J Adv Comput Res.* 2014;4:481-486.

28. Shourideh AH, Bou Ajram W, Al Lami J, Haggag S, Mansouri A. A comprehensive study of an atmospheric water generator using Peltier effect. *Therm Sci Eng Prog.* 2018;6:14-26. doi:10.1016/j.tsep.2018.02.015

29. Kabeel AE, Abdulaziz M, El-Said EMS. Solar-based atmospheric water generator utilisation of a fresh water recovery: a numerical study. *Int J Ambient Energy.* 2016;37:68-75. doi:10.1080/01430750.2014.882864

30. Shublaq M, Sleiti AK. Experimental analysis of water evaporation losses in cooling towers using filters. *Appl Therm Eng.* 2020;175:115418. doi:10.1016/j.applthermaleng.2020.115418

31. Daghigh R, Khaledian Y. Effective design, theoretical and experimental assessment of a solar thermoelectric cooling-heating system. *Sol Energy.* 2018;162:561-572. doi:10.1016/j.solener.2018.01.012

32. Opoku R, Mensah-Darkwa K, Samed Muntaka A. Techno-economic analysis of a hybrid solar PV-grid powered air-conditioner for daytime office use in hot humid climates – a case study in Kumasi city, Ghana. *Sol Energy.* 2018;165:65-74. doi:10.1016/j.solener.2018.03.013

33. Sleiti AK, Al-Ammari WA, Al-Khawaja M. A novel solar integrated distillation and cooling system – design and analysis. *Sol Energy.* 2020;206:68-83. doi:10.1016/j.solener.2020.05.107

34. Giampieri A, Ma Z, Smallbone A, Roskilly AP. Thermodynamics and economics of liquid desiccants for heating, ventilation and air-conditioning – an overview. *Appl Energy.* 2018;220:455-479. doi:10.1016/j.apenergy.2018.03.112

35. Jani DB, Mishra M, Sahoo PK. A critical review on application of solar energy as renewable regeneration heat source in solid desiccant – vapor compression hybrid cooling system. *J Build Eng.* 2018;18:107-124. doi:10.1016/j.jbjo.2018.03.012

36. Chinnappa J, Crees MR, Srinivasa Murthy S, Srinivasan K. Solar-assisted vapor compression/absorption cascaded air-conditioning systems. *Sol Energy.* 1993;50:453-458. doi:10.1016/0038-092X(93)90068-Y

37. Patel B, Desai NB, Kachhwa SA, Jain V, Hadia N. Thermoeconomic analysis of a novel organic Rankine cycle integrated cascaded vapor compression–absorption system. *J Clean Prod.* 2017;154:26-40. doi:10.1016/j.jclepro.2017.03.220

38. Salihli EM, Birhan TE. Modelling and performance analysis of directly coupled vapor compression solar refrigeration system. *Sol Energy.* 2019;190:228-238. doi:10.1016/j.solener.2019.08.017

39. Klein SA. Engineering Equation Solver (EES), Version 10, F-Chart Softw. 2019.

40. Akvosphere. Akvo 36 k. 2020. Accessed January 12, 2020. https://akvosphere.com/akvo-atmospheric-water-generators/

41. Mistingcooling.com. High Pressure Misting Pump Specifications, (n.d.). Accessed January 15, 2020. https://www.mistingcooling.com/hp-misting-pump-specifications

42. Large, Lithium Ion Battery Round Trip Efficiency. Lithium Ion Battery Round Trip Efficiency-battery-knowledge | Large Power. 2019. Accessed January 06, 2020.

43. CUERgo. Thermal conditions, (n.d.). Accessed February 11, 2020. https://www.ergo.human.cornell.edu/studentdownload/DEA3500notes/Thermal/thcondnotes.html

44. Maulana M, Syuhada A, Hamdani. Flower garden trees' ability to absorb solar radiation heat for local heat reduction. In: AIP Conference Proceedings, American Institute of Physics Publisher; 2017;1855:040017. doi:10.1063/1.4985513

45. Cengel YA & Boles MA. Thermodynamics: an Engineering Approach. 8th ed. New york: McGraw Hill; 2015. doi:10.1017/CBO9781107415324.004

46. Rosen MA, Dincer I. Exergy as the confluence of energy, environment and sustainable development. *Exergy an Int J.* 2001;1:1-13. doi:10.1016/s1164-0235(01)00004-8

47. Koehl M, Heck M, Wiesmeier S, Wirth J. Modeling of the nominal operating cell temperature based on outdoor weathering. *Sol Energy Mater Sol Cells.* 2011;95:1638-1646. doi:10.1016/j.solmat.2011.01.020

48. Solar Yangtze. BIPV High Transparent Solar Panel with Mono or Poly Solar Cell. 2016. Accessed January 25, 2020. https://yangtze-power.en.made-in-china.com/product/LycQoSBEKkhd/China-200W-BIPV-High-Transparent-Solar-Panel-with-Mono-or-Poly-Solar-Cell.html

**How to cite this article:** Niaz F, Bicer Y. Annual performance assessment of an off-grid and self-sufficient sustainable climate refuge for hot arid climates. *Energy Sci Eng.* 2022;10:600–620. doi:10.1002/ese3.1025