Comparison of two storage units for a sustainable off-grid climate refuge shelter

Fariha Niaz | Manal AlShafi | Yusuf Bicer

Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar

Correspondence
Fariha Niaz, Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar.
Email: fniaz@hbku.edu.qa

Funding information
Hamad Bin Khalifa University, Qatar Foundation, Qatar, Grant/Award Number: 210023019

Abstract
Considering the broad range of applications, efficient retrieval and storing electrical energy methods are still challenging. Besides the load variations, the ever-increasing intermittent renewable energy penetration into the grid system has witnessed the system complexities. In off-grid applications, energy storage can balance electricity consumption and electricity generation to avoid voltage and frequency deviations. This research paper focuses on the energy management of an off-grid climate refuge system used for hot and arid locations with a system comparison for two routes of different storage techniques, namely flywheels and a lithium-ion battery. The proposed system can generate its power from photovoltaics and provide cooling and other auxiliaries through vapor compression cycle and water misting units with an operation of about 16 hours (ie, from 7:00 AM to 11:00 PM) on the weekdays and 12 hours on the weekends. A comparison of levelized costs is conducted for the evaluation using HOMER software. The annual energy production by solar photovoltaics for the proposed system is 20 MWh, and the annual consumption is 16 MWh. The photovoltaic-battery storage system has shown the lowest cost of electricity, corresponding to 0.761 $/kWh, and net present cost of $66,238 and is optimum in all sensitivity analysis cases.

KEYWORDS
energy storage, integrated system, microgrid, power grid, renewable energy

1 | INTRODUCTION

Nowadays, the electric system power is rapidly evolving and requires additional power generation units and transmission lines. It increases the complexity of the power system management and control. However, the growth in electric demand could lead to system operators’ power quality issues. Furthermore, the protection of power systems becomes complicated as the area expands. Efficient energy utilization minimizes energy demand; thus, resources are conserved, and a reduction in CO₂ emissions and operating costs is possible. Estimation shows that in 2035, it will be possible to reduce 44% of global emissions by enhancing the industry process energy efficiency. Energy consumption growth, recent advances in environmental consideration, and technology generation lead to renewable energy applications, for example, new small-scale electrical energy storage (EES). Renewable sources of energy are generally network dispersed and are known as distributed. By increasing these...
units’ penetration because of distributed grids’ (DGs) stochastic behavior and small capacity, numerous issues may occur in microgrids (MG), such as supply and demand imbalance and power quality. To prevent these shortcomings of DGs, the application of energy storage systems acts as a preferable solution. Hence, it stores and injects energy into MG and power systems when needed. Besides, renewable energy sources’ (RES) intermittency demands integrating the system with reliable storage systems to use energy when there is less or no energy production source.

Chen et al have focused mainly on the hybrid photovoltaic (PV) EES systems to supply and generate power for buildings. It was shown that the supercapacitor, flywheel, and lithium-ion batteries indicate impressive prospects in PV energy storage for buildings. Shen et al have considered the MG DC system for PV generation in electric vehicle charging station, as it focuses on the technology of hybrid energy storage. The technology includes a battery and flywheels energy storage system (FESS). FESS is utilized for several low-frequency power and high-frequency power fluctuations stabilization.

In contrast, the battery system is being used for maintaining the balance for DC bus voltage. The analysis showed the control strategy to achieve reliable and flexible DC MG system operation. In Makkah, Saudi Arabia, an investigation was conducted to perform a hybrid energy system with diesel systems and PV. FESS was also utilized to store excess PV energy. HOMER analysis tool has assisted in studying the environmental and economic benefits of flywheels. Ramli et al have concluded that FESS’s utilization has decreased diesel fuel consumption, total net present cost (NPC), the system cost of energy (COE), and CO_2 emissions by reducing diesel generators’ operation. Barelli et al have proposed a specific residential MG composed of a PV plant and a hybrid energy storage system of a battery flywheel. Quantitative comparison was provided between two micro-grid electricals (DC and AC bus) dynamic performance architectures under various operating conditions. The results have shown that AC's architecture enhances grid interface current evolution, as it is 30% shorter for transient time and 58% of reduction for peak current value. Nadeem et al worked to integrate RES with a smart grid. The results showed that RES’s energy-efficient integration is beneficial not only for the utility company but also for the consumers. It reduces the electricity cost by 48% and reversing power flow to support the demand side management. Other studies showed how RES, together with demand-side management (DSM), can reduce the burden of electricity consumption (peak load, peak to average load) up to 22%, and it also helped to reduce in the total electricity cost. Excess energy can be shared with the preferred appliances or stored to reduce the peak load and peak-average load.

Research has included DSM schemes to avoid the lack of available power during a specific time by using different renewable resources. The results have shown that without applying the DSM schemes, the unmet load reaches 5.68% with 9 hours of fully discharge the battery. However, after using the DSM, energy losses were zero, and it has also reduced the unmet load to 0%. Another study has proposed the spatial and temporal DSM for the RES to minimize power losses, lower the electricity cost, and increase the system’s voltage quality and energy efficiency. Daily losses were shown to be reduced from 11.91 to 8.25 MWh, which is a 5.09% reduction. Another DSM technique has helped investigate the cost-effective and nondisruptive method for DSM with renewables, which immensely reduced the battery capacity. Thus, reducing the system cost by 27% with 10 hours of load deferring was allowed. To further discuss the DSM techniques—the system can employ glowworm swarm optimization and support vector machine to reduce the electricity tariffs for battery capacity. It is sufficient to reduce the price by 11.2%.

A study was conducted to supply cooling, heating, and meet energy demands for a multi-energy system. It considers the demand and supply-side management, which have reduced the energy consumption by 8.75%, and the battery capacity by 57%. Thus, it is helpful for changing weather conditions. Feedback correction also helps to rectify the fluctuation between the actual and predicted energy demands. Absorption and compression chillers’ electric load could be decreased by shifting the load to the other low-load period. Gianluca et al successfully achieved the annual cost saving of 4.06% and 4.67% on two setups through various DR strategies based on real-time pricing rules for HVAC systems.

The literature reviewed has not presented how the use of short-term storage of flywheel and of medium-term storage of battery assist in smooth and uninterrupted energy supply for an off-grid system; also, it lacks technical and economic comparison of a unique case for a small off-grid refuge that is capable of producing electricity, cooling, and misting in hot climates. Besides, annual energy production and consumption have not been considered for an off-grid system/shelter in hot and arid climate regions (Qatar). Thus, NPC and COE need to be calculated for the off-grid climate shelter. The primary purpose of the sustainable climate refuge is to provide comfort by lowering the temperature of the shelter by cooling system (vapor-compressed cooling system, fan, and water pumping system), by generating fresh water from the humid ambient air for drinking and water misting purposes and providing light in the shelter at
nighttime. It is not easy to walk to and from the tram and metro stations under Qatar’s scorching sun. Therefore, to facilitate and encourage pedestrians to take trams and trains for traveling, this research paper proposes and evaluates a sustainable climate refuge integrated with flywheels/battery storage systems to comfort the pedestrians. As the refuge system requires to function at nighttime, an energy storage system must store the proposed system’s electricity. This study’s main objectives are (a) to find the power consumption by each component in the shelter and power production by the solar PVs for each month, (b) to use the suitable energy storage system for smoother and interrupted energy supply for a sustainable off-grid climate refugee shelter, (c) to carry out an economic and technical comparison of flywheel and lithium-ion battery storage system for an off-grid refuge shelter, and (d) to select the optimized off-grid system to store the energy effectively based on economic and technical assessment.

2 | SYSTEM DESCRIPTION

The following is the description of the methods used to store the energy for the system, and it includes the description of the off-grid climate shelter.

2.1 | Energy storage methods

A flywheel is a mechanical energy storage system that can save energy for power systems when coupled to an electric machine. Most of the time, driving an electric device to have an extensive operating range is achieved by a power converter. This technology relies on the moment of inertia of the rotor and flywheel rational velocity square. The mass, radius, and length of the rotor affect the moment of inertia. When the machine works as a motor and charging device of energy storage, energy is then transferred to the flywheel. This storage system’s ability can be enhanced by either raising the flywheel moment of inertia or making it at elevated rotational velocities, or both. This system has a very long lifespan.

FESS mainly consists of a frequency inverter, flywheel, shaft, and generator motor unit, as shown in Figure 1. The system frequency inverter is for controlling the speed of the AC motor. Flywheel systems operate by accelerating a flywheel to a very high speed, maintaining the system energy as rotational energy. Once energy is extracted from the system, the flywheel rotational speed decreases because of the energy conversion principle.

FIGURE 1  Schematic diagram of flywheel storage

FESS is a short or medium ESS, and unlike battery storage, this system does not include chemicals that can harm the environment. FESS has been utilized in different studies for numerous applications and various purposes such as power quality improvement, flexible AC transmission system, power smoothing, aircraft and military projects, uninterruptable power supply systems, and integrated renewable energy resources. FESS is preferable to utilize instead of batteries for this study for numerous reasons, such as comparative measures for both batteries and FESS are presented in Table 1. FESS is suitable for a wide range of operating temperatures, unlike batteries, restricted to narrow temperature ranges. FESS is a short- or medium-type ESS that requires a minimum of 1 second and a maximum of 1 minute; therefore, the system is operated with no time delay. The maintenance
depends on the implemented bearings; if a suitable bearing is selected, then the maintenance at this rate will not be an issue. Magnetic bearings are an attractive option as they could reduce the system losses due to motor friction. In contrast, comparing the discharge time, the batteries have a higher discharge time than FESS.

A lithium-ion battery is utilized for the second scenario. A lithium-ion battery includes a graphite anode, spinel, or olivine structure, a lithium metal oxide cathode with a layered, a liquid electrolyte with a mixture of organic carbonates, additives, and salts, and aluminum or copper current collectors, and a separator of a porous polymer. The battery processes are central to allow fast charging and reliable operation and are relying on parameters like temperature and ion transport. The ions move from the cathode to the anode through the electrolyte when a lithium-ion battery is charged and the opposite when discharged.

### 2.2 Off-grid system

The proposed sustainable climate refuge system is designed to maintain pedestrians' comfort in the scorching hot summers. Solar PV panels generate electricity to provide power to the off-grid shelter, as shown in Figure 2. An efficient energy storage system must keep the system operational at nighttime or in adverse weather conditions. Here, it is considered whether lithium-ion batteries or flywheel energy storage systems are to be implemented.

Figure 3 shows the detailed sketch of the off-grid climate refuge. The solar PV's produced energy in the daytime is sent to the converter where DC is converted into AC, and then, this energy is supplied to the system. An efficient energy storage system for later use (ie, at nighttime, in adverse weather conditions, stabilize the frequency, or meet the system's peak) can store excess energy produced during the daytime. This energy storage system can be a battery or a flywheel. Here, the shelter's main component is the vapor-compression cooling system, which includes a compressor, condenser, expansion valve, and evaporator. The working fluid (R134a) passes through steps where the pressure and temperature increase and decrease according to the system's need. It

| Comparative measures | Batteries | Flywheels |
|----------------------|-----------|-----------|
| Operating conditions | Narrow temperature range | Wide temperature range |
| Carbon footprint     | Lower     | Higher    |
| Space                | Larger footprint | Smaller footprint |
| Maintenance          | Battery replacements every 3-5 years | Bearing replacement |
| Total emissions (kg CO₂/unit) | 13 349 | 6 115 |
| Discharge time       | 10 minutes-8 hours | 1 second-1 hour |
takes ambient air through an evaporator, condenses the vapors suspended in the humid air, and releases the dry cooled air out to lower the shelter's temperature, as shown in Figure 3. This system is also named as an air-water generator (AWG), condenses the humid air, and then generates water when the air temperature is 18°C, and the relative humidity is above 30%.22 The vapor-compression cooling system starts working when the ambient temperature is more than 28°C, and AWG is operational when humidity is more than 65%, mostly at nighttime. Thus, more water can be collected when relative humidity is higher in less time.

Furthermore, this shelter includes a fan and a water pumping system that works together to keep the pedestrian’s comfortable when the temperature is lower than 28°C. A fluorescent light must be turned on when the solar irradiance is less than 200 W/m² to bright up the shelter. It assists in making pedestrians feel comfortable and safe while passing through the shelter in the evening time. Therefore, the system shown in Figure 4 is running to get the electricity for space cooling, generating freshwater, and illuminating the shelter. Thus, the system will be functioning at nighttime or in bad weather conditions, once an efficient storage system is added. The system needs to be operating for 16 hours (ie, from 7:00 AM to 11:00 PM) and 12 hours on the weekends. The operating time is determined by following the already existing bus schedule in Doha (Qatar), considering temperature for cooling systems, and considering solar irradiance for turning on the lights in the shelter. For the summer days, first, the shelter starts with the fan and water misting system. When the temperature rises (more than 28°C) around 10:00 AM, the vapor compression cooling system turns on. It stays operational for 12 to 14 hours, and if the temperature is more than 25°C and below 28°C, only a fan and water misting system will be operating for 9 to 12 hours. The AWG generates more water in less time at nighttime when the relative humidity is higher than in the daytime. The bus/tram is scheduled to have a trip every 20 minutes. On average, the shelter occupancy has been taken as 15 persons per hour. The system is designed for peak consumption conditions on a hot summer day; therefore, it is expected 15 L/d will be used for drinking purposes and water misting purposes. One nozzle consumes 0.00063 L/s,23 and for each trip, five nozzles will be spraying water for 1 minute to cover the shelter, consuming 10 L/d. Hence, AWG will be operational only for 3 to 5 hours and will be able to sufficiently provide enough water to meet the water misting system’s needs and for drinking purposes. The
shelter needs light to be operational for the whole night, which will make 13 to 15 hours of its operation; more details can be seen in Table 2.

3 | METHODOLOGY

Several techniques and policies help flatten the peak energy curve and distribute the demand load over the day and meet the system demands.\textsuperscript{12,13} An energy system’s flexibility can be improved and increased by applying the DSM techniques.\textsuperscript{24} It also helps optimize the entire power system from generation to usage by setting some principles, policies, and DSM practices to meet customer demand.\textsuperscript{25} For this project, an off-grid climate refuge considers two different energy storage units to provide efficient energy and promote sustainability, as illustrated in Figure 4. The implemented system needs regular monitoring for energy management to get a stable energy supply from the energy storage system.

This study is designed for hot arid climate places like Qatar; hence the climate refuge works with solar PV and flywheel/battery storage systems. Qatar (Doha) is located at 25.171°N attitudinally and 51.319°E longitudinally. Doha receives solar energy most of the year and has a high potential to deploy solar PVs for energy production. Space cooling is the top priority and requirement of this region. This could be achieved sustainably by using solar PV and an energy storage system. The analysis was done using HOMER software.

3.1 | HOMER software

The National Renewable Energy Laboratory has developed a simulation software—hybrid optimization model for electric renewable (HOMER)—which helps in sizing, optimizing, and technoeconomic and environmental analysis of RESs.\textsuperscript{26} It can take the site-specific input data like load profile from the user and simulate the optimization and sensitivity analysis for the system. It can show the life cycle and technofeasibility results while simulating the off-grid systems. HOMER takes various scenarios and simulates until it is optimized based on NPC and COE. The sensitivity analysis part offers different parameters to be selected. The range varies, respectively, so it can study the effects of changing specific parameters. HOMER takes the input data as meteorological data, component prices and sizes, load profile, and other economic constraints.

3.1.1 | Load profile

Sustainable climate refuge’s load profile includes a vapor-compression cooling system, AWG, fan, water misting pump, and light. The load profile is distributed over the climate refuge shelter’s operational hours, that is, from 7:00 AM to 11:00 PM. HOMER takes load profile as input data and calculates the average load for a day and the peak load. This shelter was calculated for an average load of 18.46 kWh/d and a peak load of 3.52 kW by HOMER and is shown in Figure 5.
Each component load demand can be seen in Table 2. The following equations calculate the energy required by different systems in the shelter. The vapor compression cooling system/AWG can work as space cooling for the daytime when the temperature is more than 28°C. It can be used as an AWG for the nighttime—taking humid air from the atmosphere and condensing it into the water, which can be used for drinking and water misting purposes after filtering it through filters. The energy it needs to work has been calculated by the following Equation (1):

$$m_{in} \cdot h_{in} + W_{compressor} = m_{out} \cdot h_{out}$$ (1)

Here, $m_{in}$ is the mass flow rate of the working fluid (ie, R134 in this case) entering the vapor compressor cooling system, $h_{in}$ is the enthalpy of the working fluid, $W_{compressor}$ does the compressor require to work in the vapor compressor cooling system, $m_{out}$ is the mass flow rate of working fluid flowing out of the system, and $h_{out}$ is the enthalpy of the flowing out working fluid.

The shelter includes a fan, which takes the ambient air in the shelter (ie, almost 0 m/s), and the moving blades of the fan produce the air, which has higher pressure and velocity of approximately 16 m/s. The power needed by the fan can be calculated by Equation (2) below:

$$m_{Air,in} \cdot h_{Air,in} + W_{fan} = m_{Air,out} \cdot h_{Air,out} + m_{Air,out} \cdot \left( \frac{V_{exit}^2}{2} + 1000 \right)$$ (2)

where $m_{Air,in}$ is the mass flow rate of air entering the fan blades, $h_{Air,in}$ is the enthalpy of entering air in the fan, $W_{fan}$ is the power needed by the fan to do the work, $m_{Air,out}$ is the mass flow rate of air coming out through the fan, $h_{Air,out}$ is the enthalpy of the air coming out through the fan, and $V_{exit}$ is the velocity of the air exiting the fan.

The water pumping system is used along the fan to add comfort for the pedestrians. The water pumping system uses the water produced by the AWG to produce water mist along the fan to give coolness in the shelter. The power required by the water pump is given by the following Equation (3):

$$m_{water,in} \cdot h_{water,in} + W_{pump} = m_{water,out} \cdot h_{water,out}$$ (3)

where $m_{water,in}$ is the mass flow rate of water entering the pump, $h_{water,in}$ is the enthalpy of the water entering the pump, $W_{pump}$ is the power required by the pump to work, $m_{water,out}$ is the mass flow rate of the water mist coming out of the pump, $h_{water,out}$ is the enthalpy of the water mist coming out of the pump.

3.1.2 | Solar potential

For designing the system with solar PV, the solar radiation data and clearness index are required, taken from the National Aeronautics and Space Administration (NASA) using the latitude and longitude of the location. Doha received an average of 5.33 kW/m²/d solar irradiance, and clearness index ranges from 0.508 to 0.658, as shown in Figure 6. It measures the atmosphere’s clearness and is the fraction of solar irradiance that strikes Earth’s surface transmitted through the atmosphere. Table 3 shows the average monthly solar irradiance data and a detailed index for Doha, Qatar.

3.2 | Mathematical modeling

HOMER software uses different equations for each system’s components to calculate the energy production, energy storage, and compute the NPC and COE for the optimized configurations.

3.2.1 | Solar PV

Solar PVs chosen for this off-grid system is generic flat plate PVs with a rated capacity of 16 kW. HOMER calculates the energy production by the solar PV by the following equation:
where $Y_{PV}$ is the rated capacity of the PV array, meaning its power output under standard test condition (kW), $f_{PV}$ is the PV derating factor (%), $G_T$ is the solar radiation incident on the PV array in the current time step (kW/m²), $G_{T,STC}$ is the incident radiation at standard testing conditions (1 kW/m²), $\alpha_P$ is the temperature coefficient of power (%/°C), $T_C$ is the PV cell temperature in the current time step (°C), and $T_a$ is the ambient temperature (°C). Equation (4) takes the solar cell temperature $T_C$, it needs to be calculated by the following Equation (5).

$$
P_{PV} = Y_{PV} f_{PV} \left( \frac{G_T}{G_{T,STC}} \right) [1 + \alpha_P (T_C - T_{C,STC})] \quad (4)
$$

where $\tau$ is the solar transmittance of any cover over the PV array (%), $\alpha$ is the solar absorption of the PV array (%), $G_T$ is the solar radiation striking the PV array (kW/m²), $\eta_e$ is the electrical conversion efficiency of the PV array (%), $U_L$ is the coefficient of heat transfer to the surrounding (kW/m²), $T_C$ is the PV cell temperature (°C), and $T_a$ is the ambient temperature (°C). Equation (5) is a balance equation that shows the solar energy absorbed by solar PVs and energy produced by the PVs. The solar PV used has the capital and replacement costs of 2500 $/kW, and the operational and maintenance cost is 10 $/year for its lifetime of 25 years, as shown in Table 4. HOMER takes the prices of the following components when considering the capital and replacement cost of solar PV. PV panels, mounting hardware, tracking system, control system (maximum power point tracker), and wiring installation are considered for the PV panels. The replacement cost is replacing the PV system only if the project lifetime exceeds the PV system lifetime.

### 3.2.2 | Converter

The capital and replacement costs are 300 $/kW, and 10 $/year is the maintenance cost, as shown in Table 4.

### 3.2.3 | Flywheel

The energy stored in the flywheel can be calculated by:

$$
E = 0.5J\omega^2 
$$

where $\omega$ is the rotor angular velocity and $J$ is the moment of inertia which can be calculated as shown below:
where \( m \) is rotor mass (kg), \( r \) is rotor radius (m), and \( K \) is an inertial constant depending on the rotor shape. A generic 25 kWh carbon-fiber flywheel has been employed for this system. The flywheel's speed range for the rotor is 8000 to 16 000 rpm with a lifetime of 20 years. Other information can be found in Table 5.

### Battery

Lithium-ion batteries are deployed in the off-grid shelter to store the energy for night-time or lousy weather conditions. The battery's storage capacity can be calculated as

\[
C = \frac{E \cdot N_{\text{day}}}{\eta_{\text{con}} \cdot \eta_{\text{bat}} \cdot \text{DOD}}
\]

(8)

\( C \) is the battery storage capacity, \( E \) is the offloaded voltage, \( N_{\text{day}} \) is the number of days without charging, \( \eta_{\text{con}} \) is the converter yield's efficiency, \( \eta_{\text{bat}} \) is the battery yield efficiency, and \( \text{DOD} \) is the depth of discharge. LG Chem RESU lithium-ion batteries have been selected for the climate refuge having a nominal capacity of 3.22 kWh with 12.12% of the minimum state of charge. The capital and replacement costs are 1500 $/kWh, and the operational and maintenance cost for the batteries is 12 $/year with a lifetime of 10 years. Table 4 shows the costs and lifetime for each of the system components.

### NPC and COE

As we need to compare two scenarios, it would depend on the system's cost analysis. For this, we need to calculate the NPC and COE for both considered scenarios. HOMER calculates the NPC for the system by the following equation:

\[
\text{NPC} = \frac{C_{\text{ann,tot}}}{\text{CRF}(I,R_{\text{proj}})}
\]

(9)

where \( C_{\text{ann,tot}} \) is annual total cost, \( \text{CRF} \) is the capital recovery factor, \( I \) is the Interest rate, and \( R_{\text{proj}} \) is the project lifetime (\( N \)).

Also, to calculate the COE for the system, HOMER software has used the following equations:

\[
\text{CRF} = \left( \frac{i (1+i)^N}{(1+i)^N - 1} \right)
\]

(10)

The real interest rate needs to be calculated as follows:

\[
i = \frac{i_o - f}{1 + f}
\]

(11)

where \( i_o \) represents the nominal interest rate and \( f \) is the annual inflation rate

\[
\text{LCOE} = \frac{C_{\text{ann,tot}}}{E_{\text{prim,AC}} + E_{\text{prim,DC}} + E_{\text{grid,sales}}}
\]

(12)

\( C_{\text{ann,tot}} \) is the annual total cost, \( E_{\text{prim,AC}} \) is the AC primary load served, \( E_{\text{prim,DC}} \) represents the DC primary load served, and \( E_{\text{grid,sales}} \) is the total grid sales, which is taken as zero as no sales to the grid has made.

### RESULTS AND DISCUSSION

This study designs an off-grid climate refuge for two scenarios: PV-lithium-ion battery and PV-flywheels for hot arid climate areas implementation. The optimum configuration was decided by designing the off-grid system in HOMER simulation software using estimated load profile and other input parameters. Figure 7A,B shows both scenario designs for the off-grid system analyzed by the software analysis. Considering here flywheel with AC configuration, it offers a 30% reduced duration of
transient while interfacing to the network, and the current peak value is also lower in this configuration.9

By conducting the system analysis in the HOMER Pro simulation, Table 6 represents the two systems' main results (with battery/flywheels). It shows that the optimal configuration is for the off-grid system with the solar PVs of 16 kW with one unit of 25 kWh of a flywheel and 3.31 kW of the converter showing 78 494 $ of NPC and 0.979 of COE as given in Table 6. Whereas the other scenario with solar PVs of 16 kW and eight units of 3.3 kWh of batteries with 3.31 kW of converter shows, 66 238 $ of NPC and 0.761 of COE is lower than the first scenario with flywheel. The battery storage system has shown a lower initial cost than flywheels storage as it is 85 189 $. Therefore, this makes the Li-ion storage system economically favorable compared to the flywheel scenario with initial and operating costs of 52 994 $ and 1024 $, respectively.

### Table 6  The results of the two configurations of the off-grid system

| Configuration | PV (kW) | Battery (kWh) | Converter (kW) | Flywheel (kWh) | NPC ($) | COE ($) | Initial capital cost ($) | Operating cost ($) |
|---------------|---------|---------------|----------------|---------------|--------|--------|------------------------|-------------------|
| PV-battery    | 16      | 26.4          | 3.31           | –             | 66 238 | 0.761  | 52 994                 | 1024              |
| PV-flywheel   | 16      | –             | 3.31           | 25            | 85 189 | 0.979  | 78 494                 | 517.91            |
FIGURE 8  A, Costs summary of each flywheel storage component and, B, costs summary of the system integrated with flywheel storage

FIGURE 9  A, Cost summary of each component and, B, cost type summary of the system with lithium-ion battery

FIGURE 10  Monthly energy production by solar photovoltaic (PV)

FIGURE 11  Monthly energy consumption by the off-grid system
The optimal configuration has indicated that the capital cost is the highest due to the solar PVs' capital costs. The flywheel's capital cost follows it, and the lowest is the cost of the converter. As shown in Figure 8A, three components are considered for flywheels storage, where the generic flat-plate PV has shown to be the most expensive, followed by generic flywheels. The replacement cost is shown in Figure 8B because some solar PV parts need to be replaced. The other scenario with lithium-ion batteries in Figure 9B requires a high cost of operation and maintenance and needs to be continuously replaced for the smooth working of the off-grid system.

The second scenario (with batteries) is similar to the first scenario as Figure 9A represents the lithium-ion battery storage costs for the three components. It shows the generic flat PV to yield the highest cost compared to the other components. Besides, Figure 9B indicates the system costs in combination with the battery storage. Thus, unlike flywheels, batteries require periodic maintenance, resulting in additional costs due to the regular battery replacement.

Figure 10 shows the monthly energy production by solar PVs in the PV-flywheels configuration. Solar PV generates more energy in May, June, July, and August as it is the summer season for the considered site (Doha, Qatar). It receives a higher amount of solar energy in these months, and May has shown a slightly higher value than the other months. Whereas December, January, and February are the winter months, the system generates less than 2 MWh of energy. The excess energy generated from the optimal configuration is 4 MWh/year, and the unmet load is 0 kWh/year. The system has a renewable fraction of 100%. Therefore, it does not emit any greenhouse gas emissions, and there is no capacity shortage.

On the other hand, Figure 11 shows the monthly energy consumption by the off-grid climate refuge shelter system. To obtain this energy consumption profile, weekends, public holidays (Eids and National day), and Ramadan days are investigated for the study analysis. The energy consumption is the highest for July and August as these are the hottest months of the year; thus, additional space cooling is required in these 2 months. In contrast, December, January, and February are the winter months in Doha, and it demands less or no space cooling compared to the summer season. All the energy needed is for AWG to generate fresh water from the humid air or lighting purposes. As the summer months reach (May, June, July, and August), the energy demand increases since the demand for space cooling and freshwater generation increases.

5 | SENSITIVITY ANALYSIS

A sensitivity analysis is conducted to represent how critical parameters influence system performance. There are specific parameters in the optimal configuration whose uncertainty can lead toward the change in NPC and COE of the sustainable climate refuge system. The parameters selected for sensitivity analysis are electric load profile and solar irradiance as it varies by the time of the year, and they were shown to affect the system. Figure 12A shows that as the electric load increases from 15 to 27 kWh/d in the system, the NPC increases from 63,065.350$ to 126,304.400$. Also, as shown in Figure 12C, it can be inferred that increasing the value of
electric load increases the COE for the system. Besides, as the solar irradiance rises from 4.20 to 5.90 kWh/m²/d in Figure 12B, the surface plot shows that the NPC decreases, which takes the system towards more stable economics.

6 | CONCLUSION

The off-grid climate refuge system shelter is designed to keep the pedestrians’ comfort and encourage the pedestrians to take more public transport (ie, trams and trains) for traveling. This off-grid sustainable climate refuge takes solar energy and humid air to generate useful outputs like space cooling, electricity for lighting, and freshwater generation air for pedestrians’ comfort. The system needs to be functional for 12 to 16 hours each day. To keep the system operational at nighttime and in adverse weather conditions, it needs to have an energy storage system that must be efficient and cost-effective. Compared to other conventional systems, this system includes implementing an energy storage unit to store excess energy during the process efficiently. Therefore, two system scenarios are studied to compare and select the appropriate energy storage system to achieve pedestrians’ optimum comfort using HOMER simulation software. The main findings of the paper are written as follows:

- Annual energy production by solar PV of 20 MWh and consumption of 16 MWh is sufficient to meet the off-grid sustainable climate refuge’s demands.
- The Li-ion battery storage system is economically favorable compared to the flywheel with initial and operating costs of 52 994 $ and 1024 $, respectively.
- Considering flywheel with AC configuration, it offers a 30% reduced duration of transient while interfacing to the network, and the current peak value is also lower in this configuration.
- The optimal configuration of solar PV is the one with the Li-ion storage method. It has shown the lowest COE of 0.761 $/kWh and NPC of $66 238 and is optimum in all sensitivity analysis cases.
- The optimal configuration has indicated that the capital cost is the highest due to the solar PVs’ capital costs.
- There are no GHG emissions for the system because it is a 100% renewable fraction.
- Based on the sensitivity variables, the solar radiation, and electric load, it is observed that as the electric load increases, the NPC and COE increase as well. Whereas the higher the solar radiation values, the lower values obtained for both NPC and COE.

ACKNOWLEDGMENTS

The authors acknowledge the support provided by the Hamad Bin Khalifa University, Qatar Foundation, Qatar (210023019). The authors want to thank Dr. Sertac Bayhan (Qatar Environment and Energy Research Institute) for sharing his immense knowledge and valuable discussions.

NOMENCLATURE

\( T_a \) ambient temperature (°C)
\( C \) battery storage capacity
\( \eta_{bat} \) battery yield efficiency (%)
\( U_L \) coefficient of heat transfer to the surrounding (kW/m²)
\( \eta_{con} \) efficiency of the converter yield (%)
\( G_{T,STC} \) incident radiation (1 kW/m²)
\( K \) inertial constant
\( J \) moment of inertia
\( N_{day} \) number of days without charging
\( E \) offloaded voltage
\( T_C \) PV cell temperature (°C)
\( T_{C,STC} \) PV cell temperature under standard test conditions (25°C)
\( f_{PV} \) PV derating factor (%)
\( \omega \) rotor angular velocity
\( m \) rotor mass (kg)
\( r \) rotor radius (m)
\( \alpha \) solar absorption of the PV array (%)
\( G_T \) solar radiation incident (kW/m²)
\( G_T \) solar radiation striking the PV array (kW/m²)
\( \tau \) solar transmittance of any cover over the PV array (%)
\( \alpha_F \) temperature coefficient of power (%/°C)
\( \eta_e \) the electrical conversion efficiency of the PV array (%)

ACRONYMS

COE cost of energy
DOD depth of discharge
DSM demand side management
FESS flywheels energy storage systems
NPC net present cost
RES renewable energy systems

ORCID

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

REFERENCES

1. Arani AAK, Karami H, Gharehpetian GB, Hejazi MSA. Review of flywheel energy storage systems structures and applications
in power systems and microgrids. *Renew Sustain Energy Rev.* 2017;69:9-18. https://doi.org/10.1016/j.rser.2016.11.166.

2. Couvreur K, Beyne W, De Paepe M, Lecompte S. Hot water storage for increased electricity production with organic Rankine cycle from intermittent residual heat sources in the steel industry. *Energy.* 2020;200:117501. https://doi.org/10.1016/j.energy.2020.117501.

3. Katiaei F, Iravani MR, Lehn P. Micro-grid autonomous operation during and subsequent to islanding process. *IEEE Power Eng Soc Gen Meet.* 2004;2:2175.

4. Longe OM, Ouahada K, Rimer S, Harutyunyan AN, Ferreira HC. Distributed demand side management with battery storage for smart home energy scheduling. *Sustain.* 2017;9:120-133. https://doi.org/10.3390/su9090120.

5. Liu J, Chen X, Cao S, Yang H. Overview on hybrid solar photovoltaic-electrical energy storage technologies for power supply to buildings. *Energy Conver Manage.* 2019;187:103-121. https://doi.org/10.1016/j.enconman.2019.02.080.

6. Shen L, Cheng Q, Cheng Y, Wei L, Wang Y. Hierarchical control of DC micro-grid for photovoltaic EV charging station based on flywheel and battery energy storage system. *Electr Power Syst Res.* 2020;179:106079. https://doi.org/10.1016/j.epsr.2019.106079.

7. Ramli MAM, Hiendro A, Twaha S. Economic analysis of PV/diesel hybrid system with flywheel energy storage. *Renew Energy.* 2015;78:398-405. https://doi.org/10.1016/j.renene.2015.01.026.

8. Barelli L, Bidini G, Pelosi D, et al. Comparative analysis of AC and DC bus configurations for flywheel-battery HESS integration in residential micro-grids. *Energy.* 2020;204:117939. https://doi.org/10.1016/j.energy.2020.117939.

9. Javaid N, Hafeez G, Iqbal S, Alrajeh N, Alabeled MS, Guizani M. Energy efficient integration of renewable energy sources in the smart grid for demand side management. *IEEE Access.* 2018;6:77077-77096. https://doi.org/10.1109/ACCESS.2018.2866461.

10. Roy A, Auger F, Dupriez-Robin F, Bourguet S, Tran QT. A multi-level demand-side management algorithm for offgrid multi-source systems. *Energy.* 2020;119:116536. https://doi.org/10.1016/j.energy.2019.116536.

11. Kotur D, Durišić Ž. Optimal spatial and temporal demand side management in a power system comprising renewable energy sources. *Renew Energy.* 2017;108:533-547. https://doi.org/10.1016/j.renene.2017.02.070.

12. Tu T, Rajarathnam GP, Vassallo AM. Optimization of a stand-alone photovoltaic–wind–diesel–battery system with multi-layered demand scheduling. *Renew Energy.* 2019;131:333-347. https://doi.org/10.1016/j.renene.2018.07.029.

13. Puttamadappa C, Parameshachari BD. Demand side management of small scale loads in a smart grid using glow-worm swarm optimization technique. *Microprocess Microsyst.* 2019; 71:102886. https://doi.org/10.1016/j.micropro.2019.102886.

14. Luo XJ, Fong KF. Development of integrated demand and supply side management strategy of multi-energy system for residential building application. *Appl Energy.* 2019;242:570-587. https://doi.org/10.1016/j.apenergy.2019.03.149.

15. Coccia G, D’Agaro P, Cortella G, Polonara F, Arteconi A. Demand side management analysis of a supermarket integrated HVAC, refrigeration and water loop heat pump system. *Appl Therm Eng.* 2019;152:543-550. https://doi.org/10.1016/j.applthermaleng.2019.02.101.

16. Ribeiro PF, Johnson BK, Crow ML, Arsoy A, Liu Y. Energy storage systems for advances power applications. *Proc IEEE.* 2001;89:1744-1756. https://doi.org/10.1109/5.975900.

17. Chang TH, Alizadeh M, Scaglione A. Real-time power balancing via decentralized coordinated home energy scheduling. *IEEE Trans Smart Grid.* 2013;4:1490-1504. https://doi.org/10.1109/TSG.2013.2250532.

18. Ribeiro PF, Johnson BK, Crow ML, Arsoy A, Liu Y. Energy storage systems for advances power applications. *IEEE Proc.* 2001;89:1744-1756. https://doi.org/10.1109/5.975900.

19. Östergård R. Flywheel energy storage - a conceptual study [thesis]. Uppsala University, 2011. http://uu.diva-portal.org/smash/record.jsf?pid=diva2%3A476114&external=1

20. Östergård R. Flywheel energy storage - a conceptual study [thesis]; 2011.

21. Torell W. Lifecycle carbon footprint analysis of batteries vs. flywheels. Revision 0; 2015.

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

23. Mistingcooling.com, High Pressure Misting Pump Specifications. https://www.mistingcooling.com/hp-misting-pump-specifications. Accessed January 15, 2020.

24. Lund PD, Lindgren M, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. *Renew Sustain Energy Rev.* 2015;45:785-807. https://doi.org/10.1016/j.rser.2015.01.057.

25. Faruqui A, Chamberlin J. Principles and Practice of Demand Side Management. Palo Alto, CA: Electric Power Research Institute; 1993.

26. Baharamara S, Moghaddam MP, Haghifam M. Optimal planning of hybrid renewable energy systems using HOMER: a review. *Renew Sustain Energy Rev.* 2016;62:609-620.

27. IRENA. Electricity storage and renewables: costs and markets to 2030, 2017.

28. Aly AM, Kassem AM, Sayed K, Abolhassan I. Design of microgrid with flywheel energy storage system using HOMER software for case study. Paper presented at: 2019 International Conference on Innovative Trends in Computer Engineering (ITCE); 2019. doi:https://doi.org/10.1109/ITCE.2019.8646441.

**How to cite this article:** Niaz F, AlShafi M, Bicer Y. Comparison of two storage units for a sustainable off-grid climate refuge shelter. *Energy Storage.* 2021;e258. https://doi.org/10.1002/est.258