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ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

ORIGINAL RESEARCH

Sustainable Energy

Standalone hybrid PV/wind/diesel-electric generator system for a COVID-19 quarantine center

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Abstract

This work is motivated by the need in overcoming the electricity crisis in Gaza, which is initiated due to political reasons and the spread of COVID-19. Building quarantine centers is one of the most important means used in combating the COVID-19, but connecting these centers to the electricity distribution network at the appropriate time is not always possible and increases the burden on the local utility company. This article proposed a hybrid off-grid energy system (HES) to effectively energize the quarantine COVID-19 center in Gaza economically and environmentally. To achieve this aim, the estimated load profile of the quarantine center is fed to the HOMER-Pro program. In addition, the various systems components are introduced to the program, then modeled, and optimized. The developed approach was tested using a real case study considering realistic input data. HOMER-Pro program is used to simulate and optimize the system design. The results revealed the potential of the HES to provide environment-friendly, cost-effective, and affordable electricity for the studied quarantine center, as compared to just the diesel generators system. For the considered case study, it is found that the PV-wind-diesel generators HES can cover the connected load with the lowest cost ($ 0.348/kWh) in comparison to other possible HES structures. Taking into consideration the price of harmful emissions, the wining system shows a reduction of 54.89% of the cost of energy (CoE) compared to other systems. For the considered case study, it is found that a combination of 150 kW PV, 200 kW wind, and two diesel generators with capacities of 500 and 250 kW can hold 100% of the electrical load required to keep the quarantine COVID-19 center in operation. The initial capital cost of this HES is $510,576 where the share of wind energy, solar PV, inverter, and diesel-electric generators are $320,000, $83,076, $25,000, and $82,500, respectively. The replacemen cost ($55,918) is due to diesel generators. The total operation and maintainance cost (O&M) is $268,737, that is, 25.6% for wind turbines, 1.2% for inverters, and 70.7% for diesel electric generators. The PV/wind/diesel generators HES generate 1,659,038 kWh of electricity. The total energy requirement of 1,442,553 kWh, which means a surplus of 212,553 kWh of energy/year. The total energy (kWh) is an integration of energy sources which are 427,276 (25.8%), 274,500 (16.5%), and 857,263

The work is for great importance to Palestinian Ministry of Health and Palestinian energy authority. They provided us with needed information as they will consider this research results to power the proposed center.

(57.7%), due to wind, solar and diesel generators respectively. The cost of yearly consumed fuel is $437,828.769. The payback period for the winning system is 1.8 years. Finally, it is proved that the developed approach gives a reasonable solution to the decision-makers to find a fast, economic and reliable solution to energize the quarantine centers.

KEYWORDS
COVID-19 quarantine center, HOMER-pro, hybrid energy system, Palestine, solar energy, wind energy

1 | INTRODUCTION

The Gaza Strip located in Palestine (365 km^2 total area) is a narrow plain land 51 km long along the eastern coast of the Mediterranean Sea. It is home to about 1.85 million people (Figure 1) and it has very limited resources. According to the Gaza Electricity Distribution Company, the Gaza Strip electricity demand is estimated at 550 MW, the available power is only 280 MW, which is accumulated from 140 MW generated by local electrical power plant (50%), 120 MW is supplied by the Israeli Electricity Company (43%), and 20 MW (7%) is coming from Egypt. Thus, there is a 51% electricity shortage. To compensate for this deficit, the Gaza Electricity Distribution Company adopted 8 h schedule in which electricity is turned on and off, respectively.[1,2] The problem of the electric power shortage has worsened, especially with the spread of the COVID-19 virus among the residents of the Gaza Strip, which necessitated emergency measures, where the number of people infected with the disease reached around 189,837 people, and the number of deaths from this disease reached to 1691 people.[3]

COVID-19 is a highly contagious respiratory disease caused by the SARS-CoV-2 virus.[4] The first known case was identified in Wuhan, China, in December 2019.[5] The disease quickly spread across the globe, resulting in the COVID-19 pandemic. As one precautionary procedure issued by the World Health Organization (WHO) to cease COVID-19 disease, the Ministry of Health decided to reserve arrivals from outside the country in quarantine centers for 15 days until confirming that they are not infected with the virus. For this purpose, the Ministry established three quarantines centers next to the crossing points in the Gaza Strip (Figure 1), and of course, provided these centers with electrical appliances such as air conditioners, water heaters, lighting, television, refrigerator, and a washing machine to make the stay in these centers comfortably. With a power outage that reached 11 hours per day for the year 2021,[6] it was necessary to find a reliable source of energy as an alternative to the grid in order to supply the quarantine centers with electrical power during the intervals of a power outage. Moreover, it has been shown that COVID-19 spread fast in air polluted areas.[7]

Thus, it has been suggested to frustrate the further spread of the COVID-19 pandemic, extensive research should be developed to increase renewable energy production as a cornerstone for supporting sustainability.[7] This presents the motivation behind the present research. Renewable and environmentally friendly sources of energy become a necessity to replace depleted and polluting fossil fuels in various applications.[8,9] In Reference 2, the authors studied the acceptance of using solar energy as a replacement for conventional fossil fuels in Gaza, Palestine. Results show that people have a strong tendency to use solar energy as a replacement for traditional fuel since it is abundant and environmentally friendly. Moreover, Reference 10 studied the implementation possibility of the solar system in the household in Gaza. Results show that Gazans have a great interest in implementing solar systems in their houses. The most promising sources of renewable energy in Gaza-Strip are solar, wind, biomass, and geothermal energies.[11]

Renewable energy potential in the Gaza Strip is investigated in many works, such as References 1,12–21. However, the drawback of using renewable energy specifically solar and wind energies is their variability from season to season and even during the day.[22] Thus, an integration of several energy sources (HES) is recommended. It has become certain that the urgent shift from conventional electricity generation to HES leads to mitigating global warming and the climate change effects.[21,23,24]

In Palestine, only a few studies related to HES were performed. Alaydi presented a parametric study of solar and wind energy in the Gaza Strip in which wind power was compared with solar irradiance. Results showed that a large stand-alone PV or wind energy converter will be needed to supply the peak demand in the months from June to September.[26]

Abutaha and Shaheen investigated the different possibilities of photovoltaic solar/diesel generators HES at Nasser Hospital in Gaza.[27] The simulation results showed that the new HES decreases both operational costs and toxic emissions.[27] Al-Najjar et al introduced an HRES of PV/biomass for the Gaza Strip using simulation HOMER-Pro-software. The results showed that the optimum solution with at least $2.30 M net present cost (NPC) and $0.438/kWh cost of energy (CoE).[21] In a different study, researchers proposed PV/battery/diesel generators off-grid HES as a power source for the Islamic University of Gaza.[28] A review of the challenges and opportunities of solar and wind energy HES is given by Al Badawi et al.[29] Major power quality issues are voltage and frequency fluctuation, and harmonics for both grid-connected and stand-alone systems.[30] These can be mostly overcome by choosing the suitable design, advanced control systems and optimization of HES.[29]

Worldwide, several studies have been conducted to investigate different types of HESs. An example of HES is an energy system that produces energy from a solar system, storage battery and electrical

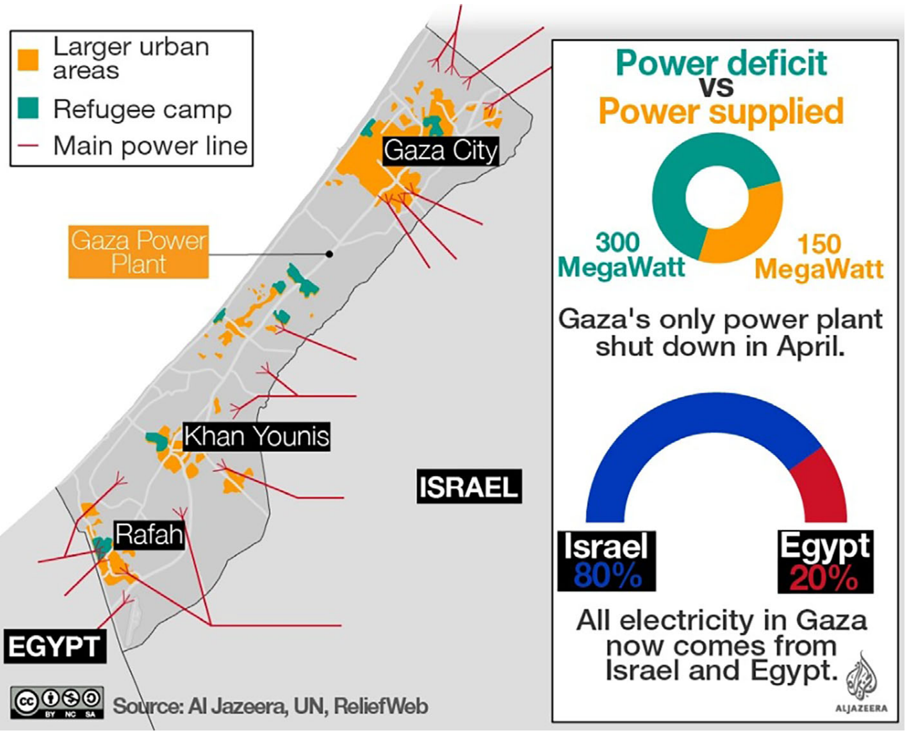

FIGURE 1 Location of COVID-19 quarantine center in Gaza and the power deficit across the strip's cities[25]

generators.[31–33] Sawle et al provided a review of HES based on PV and wind sources of energy with a comparative analysis with an off-grid hybrid system.[34] Others take benefit from the site's topography and used the pumped hydropower as potential-energy storage integrated PV/wind HES to supply 1.2 MW of electricity to a community in the southern region of Libya.[35]

A feasibility study has been conducted by Fazelpour et al for using various hybrid energy systems in order to assess the power requirements of a 125 rooms hotel on Kish Island.[36] Babatunde et al gave an analysis of off-grid PV/wind/battery/gasoline electric generators for a single residential apartment owned by a low-income earner in particular technical, economic and environmental considerations.[32] The obtained results assured that HES is a promising technology with high efficiency, environmentally friendly and affordable for low-income household, compared with using gasoline electric generators alone.[32] In a different research, the authors performed a feasibility study of electrical energy needs using PV/wind/battery HED for a household in Qeshm Island Iran using HOMER-Pro. The obtained results suggested that the optimal configuration based on the lowest NPC and CoE is PV/wind HES with battery storage.[37] Different proposed energy systems consisting of PV/wind/diesel electrical generators are studied for a village in Saudi Arabia.[38] Palej et al provided a detailed analysis of PV/wind HES connected to the grid.[39] Sarkar et al developed and analyzed using HOMER-Pro an integrated HES based on PV/wind/biomass/vanadium redox flow battery (VRFB) storage to satisfy daily energy demand.[40]

Goswami et al in their article developed a grid-connected solar-wind HES to supply power to Sagar Island in India.[41] The developed hybrid renewable energy system (HRES) power plant will provide uninterrupted power to the island. The HES will also help the environment by reducing CO_2 emissions by 1894.08 Tons annually and also will save 587.39 tons of coal in its lifetime.[41] In another work, Goswami and Sadh[42] proposed a floating solar photovoltaic system for wastewater treatment systems as large water surfaces are available. Their experimental study revealed that floating solar photovoltaic systems performed with 9.84% higher efficiency than land-based PV modules. This is a very interesting result to consider in future studies.

Halabi et al in their study considered two decentralized power stations in Sabah, Malaysia; each contains a different combination of photovoltaic (PV), diesel generators, system converters, and storage batteries.[43] Their results show that the Hybrid PV/diesel/battery system has the best technical performance compared to all other scenarios.[43] A study presented by Hossain et al used HOMER-Pro software to determine the optimal stand-alone HES for a large resort center located in the South China Sea, Malaysia (SCSM).[44] The best optimized stand-alone HES they obtained comprises PV, wind, diesel generator, converter and battery. The optimized system resulted in a cost of energy (COE) of $0.279/kWh.[44] A review of off-grid systems for rural electrification in developing countries is presented by Mandelli et al.[45] Olatomiwa et al[46] present in their article a comprehensive review of both the standalone hybrid renewable energy systems and the grid-connected hybrid renewable systems approaches as given in many papers, with focus on different HES configurations. A list of other studies that conducted the HESs have been carried out in different areas in the world is given in Table A1. The authors seek through demonstrating the experiences of other countries in Table A1 to prove the reliability of utilizing the HESs in the Gaza Strip. Thus, it can be a part of the solution to overcome the electrical crisis that Gaza suffers since 2005.

Nowadays, the HES becomes a competition variant in the energy market even in low-income countries (such as Palestine), and is cost-

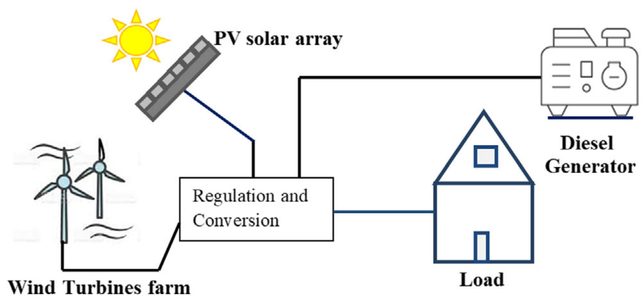

FIGURE 2 The layout of the proposed hybrid off-grid energy system

effective compared to diesel fueled generators which makes them very attractive for wide exploitations instead of diesel generators.[32] HES may be a stand-alone or on/off-grid system. This selection depends on parameters such as grid availability, cost of grid-supplied electricity, and the potential of the renewable energy resource in the application site.[47] The significance of the present paper lies in proposing a hybrid system to generate electric power, completely independent of the public electricity grid for COVID-19 quarantine centers. Therefore, this study is the most comprehensive in this field. In this context, it is believed that the present study has the following contributions:

1. Highlighting the technical, economic and environmental feasibility of hybrid renewable energy resources in Gaza-Strip;
2. Proposing the first HES that consists of three sources of energy in the country;
3. Providing the optimum design parameters of a HES consists of PV/wind/diesel generators to provide 100% of electrical energy for a COVID-19 quarantine center in Gaza-Strip;
4. Proving the capability of the local renewable energies to be a part of the solution in overcoming the economic and social crisis the sector is experiencing as a result of the electricity deficit;
5. Calculating The payback period and
6. Estimating the cost of producing energy from HES considering the cost of an environmental hazard.

2 | METHODOLOGY

The considered simulated hybrid renewable energy system consists of a wind turbine, photovoltaic (PV) array and diesel generators. Diesel generators, exist on the site, are used as a base and backup unit for the considered system. Therefore, we did not consider adding batteries. The considered system is designed specifically for an off-grid case. The data required for solar and wind resources for the designated site were taken from online data of the NASA methodological department.

2.1 | Modeling of the HES system

The proposed system to be studied (Figure 2) consists of a PV system, wind turbines, and two diesel generators (DGs) as well as the connected loads. The mathematical models of the major components of the system are presented in section 2.2.

2.2 | Scheme of the proposed HES

2.2.1 | PV solar energy system

The PV panel is the responsible party of the solar system to convert the solar power into an electrical one. The produced power by a PV panel is calculated as follows[48]:

$$P_{PV} = (P_{STC} + \zeta_P (T_{Cell} - T_{STC})) * \frac{H_t}{H_{STC}} \quad (1)$$

where P_{PV} represents output power, P_{STC} is the nominal output energy at standard test condition (STC), T_{cell}, T_{STC} are the temperature of the PV module and the STC cell temperatures, respectively. ζ_P is the power temperature coefficient (W/°C), and H_t and H_{STC} are the global and STC solar radiations, respectively.

2.2.2 | Wind energy system

The generated power by a wind turbine varies with wind speed and wind turbine structure. Based on Reference 33, the generated power by a wind turbine can be formulated as follows:

$$P_{wind} = \frac{1}{2} \rho A V C_p(\lambda, \beta) \eta_t \eta_g \quad (2)$$

ρ is the air density, A is the rotor area in m^2, V is wind velocity in m/s, C_p is the performance density of air coefficient of the turbine and η_t and η_g are the efficiencies of the wind turbine and the generator, respectively.

2.3 | HOMER-Pro software

The HOMER software is used to model and perform the determination of optimal sizing and operational strategy for a hybrid renewable energy system based on simulations and optimization.

2.3.1 | HOMER-Pro simulation

Design of the considered system based on the selection of components by the design engineer. In this process, energy balance calculation will be performed by HOMER-Pro based on the system configuration comprising several numbers of sizes of the component. Here, the considered components are PV array, wind turbine, and diesel generator for the purpose of analysis. After simulation, it determines the best optimal system configuration which is suitable to provide the energy demand. HOMER-Pro will simulate the designed system based on the estimation of installation cost, replacement cost, operation and maintenance cost, fuel and interest rate.[49,50]

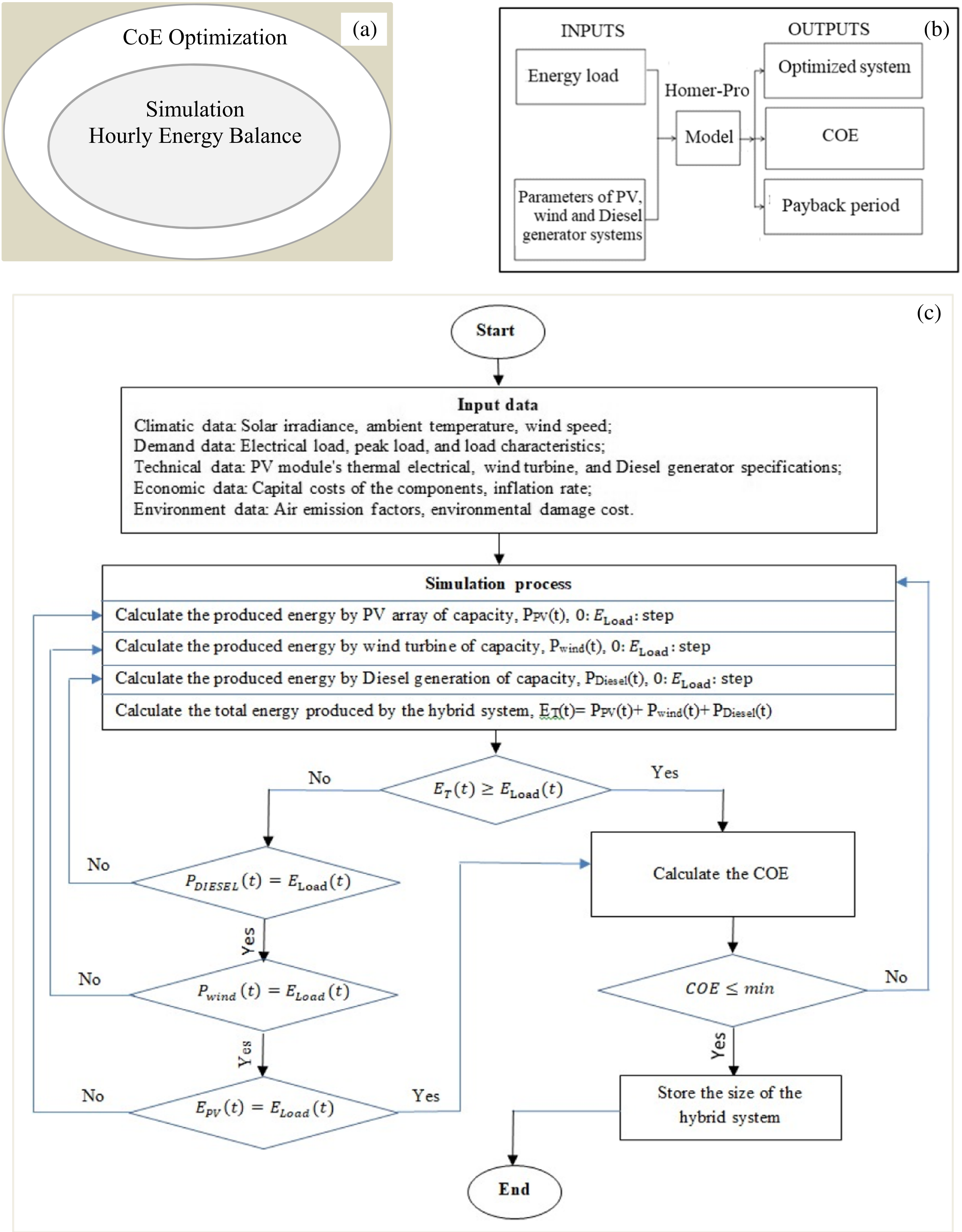

FIGURE 3 (a) Interactions between simulation and optimization (b) key information for modeling (c) flowchart presents the optimization process used by HOMER-Pro

2.3.2 | HOMER-Pro optimization

The optimal solution is obtained after simulating the entire possible number of selections of hybrid renewable energy system configuration. A list of configuration results is displayed in a sorted form considering NPC and CoE. HOMER is utilized to analyze the different types of system configurations from the lowest to the highest NPC value.[49,50]

2.3.3 | Optimal design approach

The load inputs are given to the Homer-Pro system to do the simulation and obtain the optimal design. Figure 3a shows the interaction between simulation and optimization, and Figure 3b presents key information for the modeling. Figure 3c gives a detailed flowchart of the process of optimization of the system using HOMER-Pro.

TABLE 1 Typical appliance rating power in a quarantine center[a]

Electrical device	Power (W)	Quantity	Operating hours (h/day)	Energy consumed kWh/day
Air conditioner 12000 BTU	1060	165	9	1574.1
Heater (40 L)	2500	165	3	1237.5
Heater (2 L)	2200	165	1.5	544.5
Refrigerator (6 cu. ft)	150	165	9	222.8
Washing machine	1500	16	12	288
Inner light	40	165	9	59.4
Outer light	100	20	13	26
Total energy consumed				3592

[a]Meeting with the head of the safety health department (Ministry of Health).

As discussed before, the HES system should be designed to cover the connected loads economically and environmentally in simultaneous way. In the proposed approach, the PV system size PV_{size}, the diesel generator size DG_{size}, the number of the diesel generators N_{DG}, and wind turbines number N_w should be optimized to minimize the capital cost of energy and the harmful gas emissions. Therefore, the optimal design problem can be formulated as follows:

$$\min_{PV_{size}, DG_{size}, N_{DG}, N_w} CoE + Gas_{em} \quad (3)$$

Subject to:

$$PV_{size.min} < PV_{size} < PV_{size.max};$$

$$N_{w.min} < N_w < N_{w.max};$$

$$DG_{size} \in DG_{set.given}$$

$DG_{set.given}$ is the given set for the possible diesel generators to be installed by the user. Moreover, the CoE equals the total-annualized cost of the consumed energy $C_{ann.tot}$ divided by the total served energy by the system E_{served} as follows:

$$CoE = \frac{C_{ann.tot}}{E_{served}}. \quad (4)$$

In addition, the harmful gas emissions that include carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons, particulate matter, sulfur dioxide, and nitrogen oxide are studied.

2.4 | Case study

2.4.1 | Proposed site

HES is proposed to power the quarantine center (Figure 4) locate in Dier El Balah city in the middle of Gaza-Strip, Palestine. This information is fed to HOMER-Pro to get data about solar irradiance and wind speed in the region. Presently, the quarantine center is powered by two diesel generators and by a power line from the Gaza electricity distribution company (GEDCo). Gaza imports diesel causing a high price for electricity production by a diesel generator and urging the exploration of renewable energy as an alternative to meet load demands. The input data, used to simulate and analyze the HES as well as the design results of different HES configurations, are discussed in the following sections.

FIGURE 4 Dier El-Balah quarantine center[51]

2.4.2 | Electrical load

The Palestinian Ministry of Health recommended 14–21 days as a quarantine period. Therefore, the appliances for each tenant in the quarantine center should provide an adequate comfort level during the infected person's stay. In this study, air conditioners, heaters, refrigerators, washing machines, and lights are the specified appliances for a tenant in the quarantine center. The estimated power consumption[*] of the presented appliances are listed in Table 1. The load demand is measured and plotted as shown in Figure 5.

*The interviews made with the tenants.

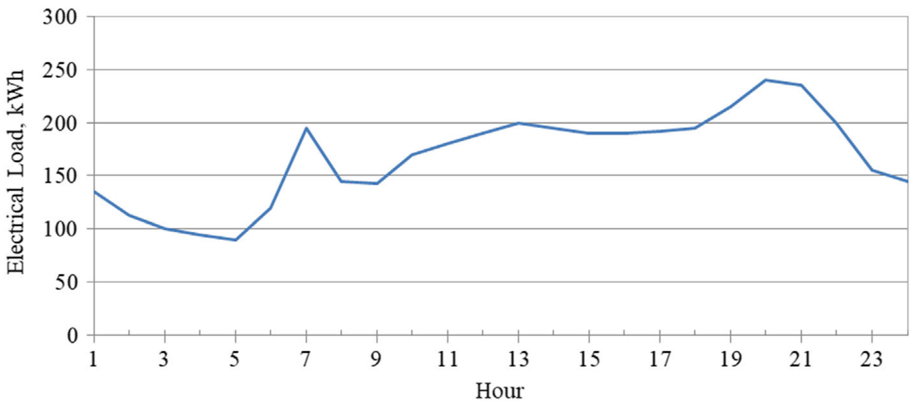

FIGURE 5 Daily electrical load profile for the study site

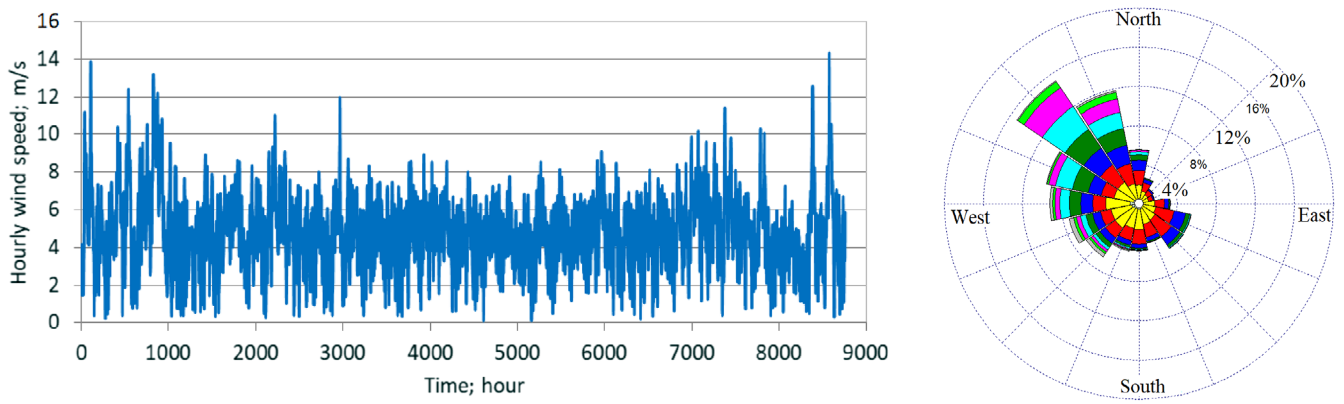

FIGURE 6 Hourly wind speed and wind rose at the study location

2.4.3 | Wind speed

Wind speed is obtained from the HOMER-Pro website. Figure 6 exhibits the hourly wind speed and the wind rose at an altitude of 30 m above the ground level for the study site. It can be seen from Figure 6, that the site experiences minimum and maximum average speed values of 3.99 m/s and 5.41 m/s in August and February respectively. The average yearly wind speed is around 4.68 m/s.

2.4.4 | Solar radiation

Solar radiation and temperature data are taken from the HOMER-Pro website. The hourly global horizontal irradiation (GHI) at the site is used to calculate the output of the flat panel PV array as in Figure 7. The maximum solar radiation occurs in summer (June and July) with an average of 7.985 kWh/m^2/day/year. The annual average solar GHI is equal to 5.57 kWh/m^2/day.

2.4.5 | Ambient temperature

Ambient temperature is playing a crucial role in energy systems design.[52,53] It can also be seen explicitly from Equation (1). Figure 8 presents a contour plot of the hourly air temperature of Dier El Balah. August is the hottest month with temperatures ranging from 24 to 32°C. While January is the coldest month with temperatures varying from 9 to 18°C. The year around mean temperature is considered 24°C.

2.4.6 | Assumptions, limitations and uncertainties

The following assumptions are considered in the present work to facilitate the simulation process:

1. A fixed operating cost which includes maintenance, insurance and labor costs in addition to fuel cost for diesel generator;
2. Constant efficiencies for all systems;
3. The land and land preparing costs are not included;
4. The degradation rate is taken constantly during the lifespan 0.2%.
5. The O&M costs included all daily or periodic expenses, including workers' salaries, taxes, and so on.

The major sources of uncertainty are data availability, model selection and parameter estimation. It was reported that the uncertainty values for global solar irradiation are 2%–5% for ground measurements and for satellite-derived data, respectively.[55] This value will

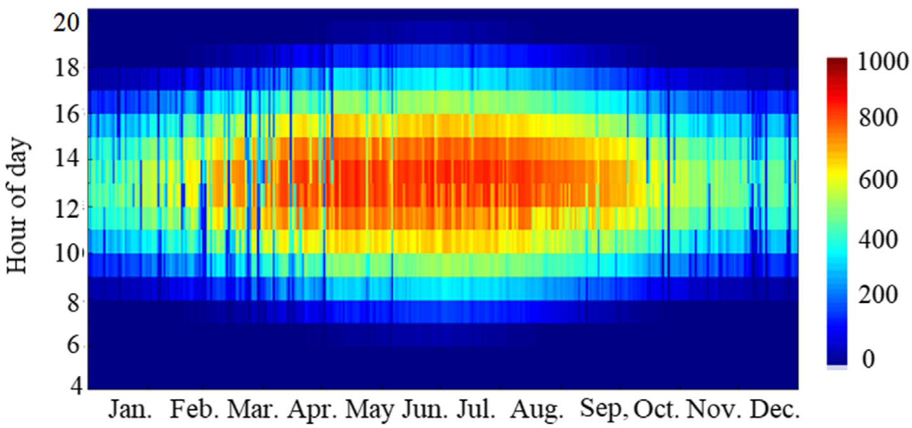

FIGURE 7 Hourly global horizontal solar irradiance at the study site

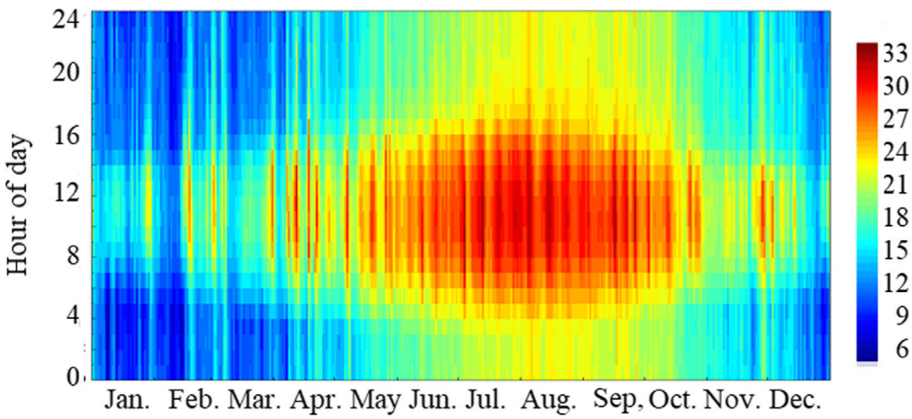

FIGURE 8 Hourly ambient temperature at the study site[54]

be exacerbated when the horizontal solar radiation is converted to tilted one by using the transposition models.[56] The price of renewable energy facilities is also considered a source of uncertainty. Nassar and Alsadi[12] reported that the variance in the prices of the PV modules exceeded 360%. Also, the rate of exchange is one of the uncertainty sources in the results, especially in research that uses several currencies, which must eventually be converted into one currency. The main limitation of the present study is that it does not provide a sensitivity analysis of the effect of various design and operating parameters and their weights on the decision.

3 | PROPOSED HYBRID ENERGY SYSTEM DESIGN OPTIONS AND RESULTS

In this section, four different schemes are presented in which the base system is considered the two diesel-electric generators, the second system consists of wind/diesel generators HES, the third system consists of PV/diesel generators HES, and the fourth system is PV/wind/diesel generators HES as in the following subsections.

The obtained results from HOMER-Pro software are presented in Figure 9 including hourly yields of 150 kW capacity PV solar system, wind turbine of 200 kW capacity and two diesel generators with 250- and 500-kW capacities as compared to the electric load. The operation regime, behavior and the rated power obtained by each source are plotted as a series view in Figure 9.

3.1 | The power system consists of two diesel electric generators

The techno-economics analysis for two AC-diesel generators with 500 kW (CAT-500 kW) and 250 kW (CAT-250 kW) ratings (current situation on site) is conducted using HOMER-Pro. Both generators have 20,000 h lifetimes, 25% minimum load radio, and $1.47/l fuel cost. Additional costs related to 500 and 250 kW generators are $120/kW and $60/kW capital cost, $90/kW and $45/kW replacement cost, and $1/h and $0.5/h operation and maintenance cost (O&M), respectively. Figure 10 presents the schematic diagram of the proposed design where the two generators are connected to the load via the AC bus line.

Table 2 displays HOMER-Pro simulation results where the first and second row shows the results when using two generators vs. one generator second row, respectively. Table 3 indicates that the optimal cost of electric energy occurs when operating the two generators and equals $0.43/kWh. In this case, CAT-500 kW and CAT-250 kW operated for 1248 and 7512 h per year respectively and 413,184 liters of fuel were used which is lower than the system with only CAT-500 kW. The net present cost of the optimal system as calculated by HOMER-Pro is $8.06 M, which is lower than the net present cost of the system only CAT-500 kW which is $ 9.3 M. The optimal system has lower CO_2 (kg/year) emission compared to a base system where it is found the optimal system emits 1,091,681 kg/year and the base system emits 1237,331 kg/year.

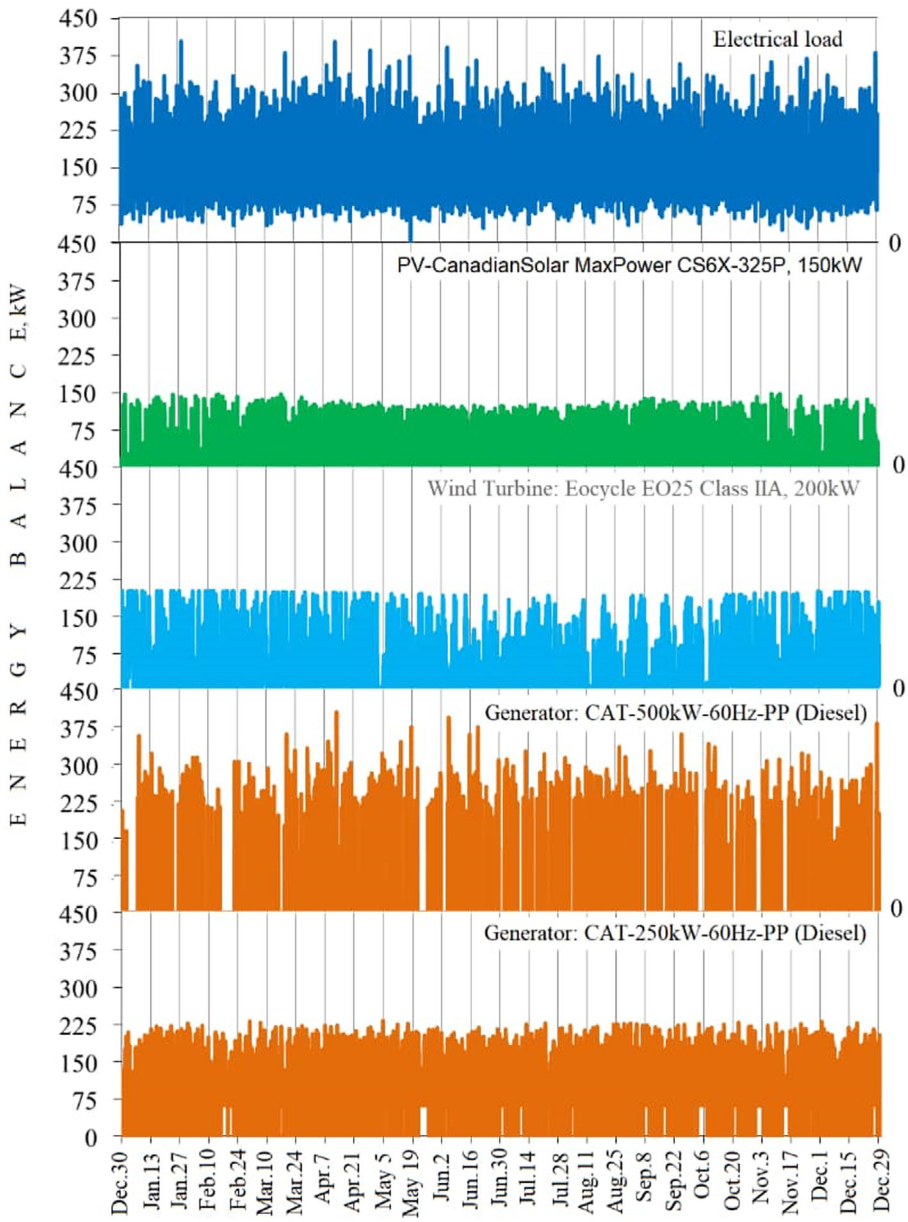

FIGURE 9 The Hourly electrical production of 150 kW PV solar system capacity, 200 kW wind turbine capacity, 250 and 500 kW diesel generators capacities as compared with the load capacity

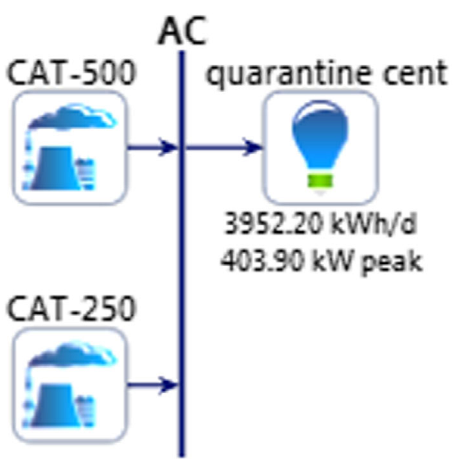

FIGURE 10 Diesel electric-generators-based system

Table 2 lists the value of total energy generated in 1 year (1,444,039 kWh/year), jointly produced by the two generators where 22.5% and 77.5% of energy production was generated by CAT-500 kW and CAT-250 kW generators, respectively. Accordingly, there is 1486 kWh/year of excess energy. It is also noticed that there is a reduction in the cost by $1,235,656 in favor of the optimized system.

3.2 | Wind/diesel electric generators HES

To reduce diesel consumption and mitigate the environmental impact in Gaza-Strip, the system analyzed in section 3.1 is integrated with wind turbines (referred to by ES25IIA in Figure 11) each has three blades and produces 25 kW. It is assumed that the wind turbine capacities are taken to be 25, 50, 75, 100, 125, 150, 175, 200 kW to 500 kW. Thus, for example, the accumulated power by eight wind

TABLE 2 Simulation results of diesel only case

CAT-500 (kW)	CAT-250 (kW)	Cost/ CoE ($)	System/ total fuel (m^3/yr)	CAT-500/ hours	CAT-500/ production (MWh)	CAT-500/ fuel (m^3)	CAT-500/fuel cost ($/yr)	CAT-250/ hours	CAT-250/ production (MWh)	CAT-250/ fuel (m^3)	CAT-250/fuel cost ($/yr)	Cost/ NPC ($)
500	250	0.43	413	1248	326	93	137,257	7512	1119	320	470,123.5	8,061,773
500	-	0.50	468	8760	1509	468	687,637	-	-	-	-	9,297,429

turbines is 200 kW. The wind turbine considered in this study has a 30 m rotor diameter and 30 m height and 20 years lifetime. The cut-in wind speed and rated speeds are 3.5 and 12 m/s, respectively. The capital cost and O&M costs are $40,000/year and $2000/year, respectively for each wind turbine.

Table 3 displays the HOMER-Pro simulation results of the proposed system. The optimal HES consists of two diesel generators and 8 wind turbines with the minimum cost of energy (CoE) ($0.377/kWh). This is lower than the CoE of the diesel generators only (CoE = $0.43/kWh). It can also be noticed that via using wind/diesel electric generators HES, there is a reduction in consuming diesel by 332,164 liters compared to using the diesel-electric generators only which consume 413,184 liters saving of 81,020 liters/year. Moreover, the total diesel generator operating time in the optimal system is lower than the operating time of diesel-electric generators only system by 30 h in the year where this system operates 8730 h while diesel only system operates 8760 h. The HES produced 1,538,335 kWh electricity/year, 28.2% produced by wind turbines, 11.8% and 60% of energy produced by 500 and 250 kW generators, respectively. Excess energy equals 95,782 kWh/year is produced by wind/diesel electric generators HES as compared with the base system. The total capital cost of the wind/diesel electric generators HES equals $402,500/year and the total replacement and O&M costs are $5295/year and $268,065/year, respectively. The replacement cost for wind turbines and diesel generators are considered zero and $52,952/year, respectively. Further, the O&M costs for wind turbines and diesel generators are $206,840/year and $61,225/year, respectively. In addition, Table 3 shows a reduction in the net cost as we add renewable energy sources which have participated by 23.4% in the optimal system.

3.3 | PV/diesel electric generators HES

In this section, a solar PV/diesel-electric generator HES is proposed (Figure 12) and analyzed using HOMER-Pro. In Figure 12, CS6X represents PV panels. The load data and diesel generator inputs are kept the same as in section 3.1. Solar radiation data, discussed in section 2.4.4, and PV panel-related technical specifications (Table 4) have been considered as input. A 30 years lifetime 325 W PV panel cost is taken as $180. PV efficiency is 16.17%, and its derating factor is 80%. The replacement cost and the capital cost are chosen to be equal and $1/year per PV panel is assigned for O&M cost. The PV is assumed to have a 30.9° tilt angle (angle with the ground). The total capacity of the PV panel and inverter capacity is ranged 25, 50, 75, 100, 125, 150, 175, 200 kW till 500 kW. The inverter cost equals $5000/30 kW and its maintenance cost is $0/year/30 kW. The technical specifications of the inverter are listed in Table 4. The lifetime and efficiency of the inverter were 20 years and 93%, respectively.

Table 5 shows that the optimal solution (from HOMER-Pro analysis) has a minimum CoE equal $0.38/kWh which consists of 150 kW PV, 150 kW inverter and two generators. The CoE for this system is lower than for a diesel-electric generator system but higher than for wind/diesel-electric generator HES. In the PV/diesel-electric generator HES, 16.6% of total energy is produced by PV systems. Diesel consumption was increased to 357088.26 L compared to 332,164 L for wind/diesel-electric generator HES but lower than 413,184 L for diesel generators only system. Thus, the PV/diesel electric generators HES saved 56,096 L compared with the diesel generators only system.

The solar PV panels produced a total of 274,500 kWh while diesel generators produce 1,203,219 kWh of electricity for a total of 1,477,719 kWh during 1 year of operation. This means that solar energy and diesel-electric generators contributed by 16.6% and 83.4% of the total energy, respectively. Of this total energy, 28,857 kWh (1.95%) is surplus. The total capital cost of the HES is $190,577 as follows; $83,077 PV system cost, $25,000 invertor cost, and $82,500 diesel generators cost. The replacement cost of HES is $67,382 due to diesel-electric generators and PV system and zero for invertor. The O&M cost of the HES for 1 year is $67,501($1293 for PV, $63,623 for diesel-electric generators, and $2586 for the inverter).

3.4 | PV/wind/diesel electric generators HES

Figure 13 displays a PV/wind/diesel-electric generator HES. In HES, the wind turbine capacities are taken to be 25, 50, 75, 100, 125, 150, 175, 200 kW till 500 kW; PV system capacities and inverter capacities are taken similarly, and the two diesel generators capacities are 250 and 500 kW as they are given by the site operator. These values are fed to HOMER-Pro software as input. The simulation is done using HOMER-Pro which revealed the optimum HES with minimum CoE. Table 6 presents the simulation results that showed PV/wind/diesel electric generators HES have a minimum CoE of $0.348/kWh. The wining system consists of eight wind turbines (200 kW), PV panels (150 kW), an inverter (150 kW), and two diesel generators (750 kW). The initial capital cost of this HES is $510,576 where the

TABLE 3 Simulation results of wind/diesel HES

EO25IIA	CAT-500 (kW)	Architecture/ CAT-250 (kW)	Cost/ CoE ($)	System/ total fuel (m^3/yr)	CAT-500/ Hours	CAT-500/ production (MWh)	CAT-500/ fuel (m^3)	CAT-500/ fuel cost ($/yr)	CAT-250/ hours	CAT-250/ production (MWh)	CAT-250/ fuel (m^3)	CAT-250/fuel cost ($/yr)	EO25IIA/ production (MWh/yr)	Cost/ NPC ($)	System/ renewable fraction (%)
8	500	250	0.38	332	742	182	53	774,70	7988	923	280	410,811	433	7,034,956	23.4
	500	250	0.43	413	1248	326	93	137,257	7512	111,9	320	470,124		8,061,773	0
8	500		0.48	419	8730	1308	419	615,876					433	8,895,312	9.3
	500		0.50	468	8760	1509	468	687,637						9,297,429	0

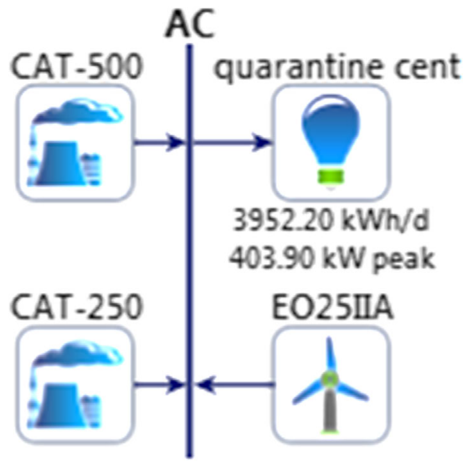

FIGURE 11 Wind/diesel hybrid off-grid energy system

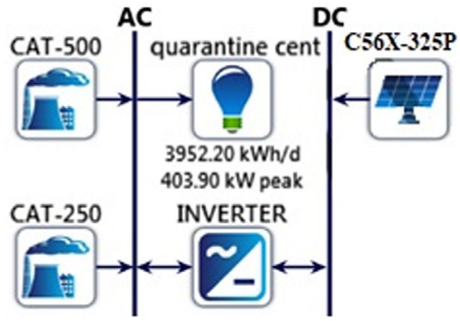

FIGURE 12 PV/diesel hybrid power system

share of wind energy, solar PV, inverter, and diesel-electric generators are $320,000, $83,076, $25,000, and $82,500, respectively. The replacement cost ($55,918) is due to diesel generators. The total O&M cost is $268,737, that is, 25.6% for wind turbines, 1.2% for inverters, and 70.7% for diesel electric generators.

The PV/wind/diesel generators HES generate 1,659,038 kWh of electricity. The total energy requirement of 1,442,553 kWh, which means a surplus of 212,553 kWh of energy/year. The total energy (kWh) is an integration of energy sources which are 427,276 (25.8%), 274,500 (16.5%), and 857,263 (57.7%), due to wind, solar and diesel generators, respectively. The cost of yearly consumed fuel is $437,828.769.

Accordingly, the total monthly accumulated energy generated by a HES consisting of PV/wind/diesel electric generators is depicted in the form of stacked bars as shown in Figure 14.

3.5 | Economic–environmental assessment of the HES options

In this work, we present four HESs which are diesel electric generators, wind/diesel electric generators HES, PV/diesel electric generators HES, and PV/wind/diesel electric generators HES. In the analysis, the fuel cost is considered equal to $1.47/l while looking for the optimal HES with minimum CoE. The results for different HES are given in Table 7. The results show that the lowest CoE is $0.348/kWh in the case of PV/wind/diesel electric generators HES.

The utility company in Gaza-Strip, Palestine (GEDCo) that distributes energy to local customers in Gaza-strip receives energy mainly from Israel, Egypt and the only local power station. The local station relies on diesel to generate electricity, the emission factor for producing electricity is more than 0.81 kg CO_2/kWh.[59] The emission factor includes carbon monoxide, unburned hydrocarbons, particulate matter, the proportion of fuel sulfur converted to PM (%), and nitrogen oxide. According to HOMER-Pro simulation results, the types and values of greenhouse gases (GHG) (kg/year) for the proposed systems are listed in Table 8.

It is obvious that the emissions are reduced significantly when adding renewable energy resources in addition to diesel generators. The best case with the lowest harmful emission is when using PV/wind/diesel electric generators HES. The CO_2 mitigation cost saving can be calculated as follows[60,61]:

$$C_{CO2} = EF_{CO2} \times G_{elec} \times f_{ren} \times \emptyset_{CO2} \quad (5)$$

EF_{CO2} is the emission factor of CO_2 [kg CO_2/kWh], G_{elec} is the generated electrical power [kW], f_{ren} refers to the friction coefficient of the renewable energy [kW], and $\emptyset_{CO2}$ indicates to the international price of CO_2. And it is expected to be $79.10/ton CO_2 for 2022.[62]

Accordingly, calculations were carried out for all generation options, including connection with the public electricity grid, and for all HES options. Table 9 listed the obtained results.

The cost of environmental damage from an annual generating 1443 MWh is about $136,970/year from the Gaza electrical station, while from the diesel electric generators is about $92,455/year.

The new trend of economic evaluation of renewable energy systems is involving the cost of environmental damage in the CoE estimation. This way gives a fair opportunity for alternative energies to compete in the energy market.[61] A precise way for estimating CoE for

TABLE 4 PV module specifications

Item description	Value
PV panels[57]	
Brand name	Canadian
P_{max} at STC	325Wp
V_{mp}	39.1 V
I_{mp}	10.42
V_o	45.8 V
I_s	9.28 A
Module efficiency	16.17%
Operating module temperature	40°C to +85°C
Maximum system voltage	1000 V DC
Maximum series fuse rating	20 A
Price	$180
Inverter[58]	
Brand Name	STP
Max. DC power/DC-rated power	25,550 W/25,550 W
Max. input voltage 1000 V	Max. input voltage 1000 V
Output wave	Pure Sine Wave
Output voltage	230VAC
Output frequency	50/60 Hz
System voltage	48VDC
Solar charger	60A, MPPT
AC charger	60A @ 48VDC
Max. efficiency	93%

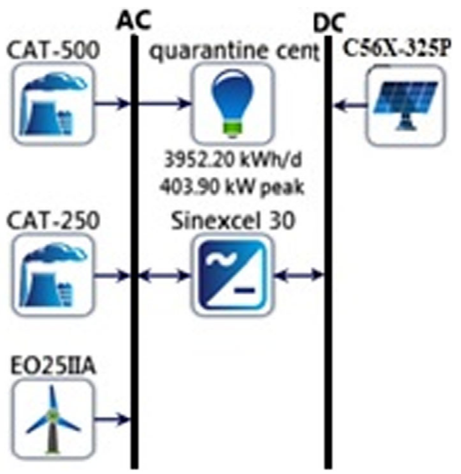

FIGURE 13 PV/wind/diesel hybrid off-grid energy system

TABLE 5 HOMER-pro results for PV/diesel HES

CS6X-325P (kW)	CAT-500 (kW)	CAT-250 (kW)	Inverter (kW)	Net present cost ($)	CoE ($)	Operating cost ($/yr)	Initial capital cost ($)	Renewable fraction (%)	System fuel consumption (m^3/yr)
150	500	250	150	7,103,314	0.38	534,731	190,577	16.59	357
-	500	250	-	8,061,773	0.43	617,232	82,500	-	413
150	500	-	100	8,741,314	0.47	663,822	159,744	5.36	433
-	500	-	-	9,297,429	0.50	714,556	60,000	-	468

TABLE 6 HOMER-Pro simulation output for PV/wind/diesel generators HES

PV (kW)	Wind converter (kW)	Diesel generator 500 (kW)	Diesel generator 250 (kW)	Inverter 30 (kW)	Cost/ CoE ($/kWh)	System/total fuel (m^3/yr)	Cost/operating cost ($/yr)	Cost/initial capital ($)	Cost/ NPC ($)	System/Ren Frac (%)	System/total fuel (L/yr)
150	8	500	250	150	0.348	298	462603.5	510,576	6,490,890	33.6	297,842.7
150	-	500	250	150	0.38	357	534530.5	190,576	7,100,728	16.6	357,088.3
150	4	500	-	100	0.46	413	642714.1	319,742.7	8,628,440	11.0	413,403
150	-	500	-	100	0.47	433	663688.7	159,742.7	8,739,589	5.3	433,109.2

specific HES installation is expressed in terms of key financial aspects as[63,64]:

$$CoE = \frac{\left[C_{PV} + C_{wind} + C_{Diesel} + \sum_{t=1}^{n} \frac{O_{PV}}{(1+r)^t} + \sum_{t=1}^{n} \frac{O_{wind}}{(1+r)^t} + \sum_{t=1}^{n} \frac{O_{Diesel}}{(1+r)^t} - \sum_{t=1}^{n} \frac{C_{CO2}}{(1+r)^t}\right]}{\left[\sum_{t=1}^{n} \frac{G_{elec}}{(1+r)^t}\right]} \quad (6)$$

where C_{PV},C_{wind},C_{Diesel} present the annual capital cost of PV, wind and diesel electric generators systems respectively. O_{PV},O_{wind}, O_{Diesel} refer to the annual O&M costs of PV, wind and diesel electric generators systems respectively. r is the discount rate (8%) and n is the lifetime (25 years). By applying Equation (6), new values for the cost were obtained. These values are tabulated in Table 10.

It is clear from Tables 9 and 10 that, increasing the renewable energy fraction coefficient will raise the share of renewables in installed HES and raise the environmental damage saving value. Accordingly, the cost of energy production is reduced. From the data in Table 10, it became clear that PV/wind/diesel electric generators HES option is the best among all the options studied, even though it is cheaper than the price of electricity provided by the Israeli company ($0.20/kWh).

3.6 | Payback period

A simple payback period is the years at which the cash flow difference between the winning HES and base HES changes signs from negative to positive. It measures the period it takes to recover the difference in investment costs (initial installation cost and operational cost and maintenance cost) between the two systems.[65] To calculate, the payback period of the generated 1,659,038 kWh of electricity of the winning HES, PV/diesel generators are used as the base system (first and last row in Table 6).

Table 11 displays different costs for both systems. Where the wining system has CoE lower by $0.121/kWh than the base system. This means that increasing the renewable energy share in the hybrid system produces a safer and more affordable system. The NPC difference between the two systems is $2.25 M indicating that the winning system saves money compared to the base system.

In the results obtained in this work, the internal rate of return (IRR) (%) is 55.7%, the simple payback (year) equals 1.88 year and the discount payback (year) equals 2.04. In the calculations, discounted payback year is measured as the time needed to recover the initial cost if the cash inflows are discounted to their present value.[66]

4 | CONCLUSIONS

A new Hybrid energy system for Dier El Balah quarantine center in Gaza Strip was proposed. HOMER-Pro software was used to analyze, simulate and evaluate the proposed systems. The choice of quarantine

Item	Diesel-electric generators	Wind/diesel electric generators	PV/diesel electric generators	PV/wind/diesel electric generators
Renewable Fraction, %	0	28.2	18.6	42.3
CoE, ($/kWh)	0.430	0.377	0.380	0.348
Fuel consumed, (L/yr)	413,184	332,164	357,088	297,843
Fuel cost, ($/yr)	607,381	488,281	524,920	437,829
Capital cost, ($)	82,500	402,500	190,577	510,576

TABLE 7 Comparison between different HES options

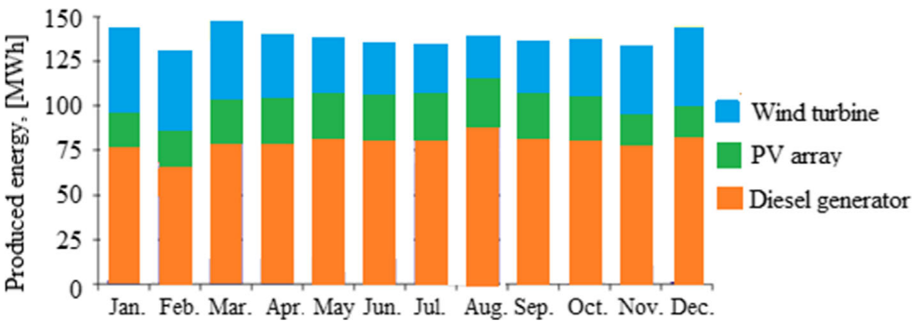

FIGURE 14 The accumulated power generated via three combinations of hybrid off-grid energy system

Pollutant (kg/yr)	Diesel-electric generators	Wind/diesel electric generators	PV/diesel electric generators	PV/wind/diesel electric generators
CO_2	1,091,618	877,475	943,404	786,803
CO	947	816	826	735
Unburned hydrocarbons	38	32.3	33.1	29.1
Particulate matter	40.8	33.9	35.4	30.5
Sulfur dioxide	2710	2179	2342	1954
Nitrogen oxides	7837	6304	6773	5653

TABLE 8 Emissions associated with each HES options

Pollutant	G_{elec} [MWh/yr]	EF_{CO2}, [ton/MWh]	f_{ren}	C_{CO2} $/yr
Diesel-electric generators	1443	0.81	0	0
Wind/diesel electric generators	1443	0.81	0.282	26,073
PV/diesel electric generators	1443	0.81	0.186	17,197
PV/wind/diesel electric generators	1443	0.81	0.423	39,109

TABLE 9 The cost of CO_2 mitigation cost saving for all options of generation

Item description	Diesel-electric generators	Wind/diesel electric generators	PV/diesel electric generators	PV/Wind/diesel electric generators
CoE $/kWh	0.430	0.253	0.296	0.157
Percentage of reduction in CoE value; %	0	32.9%	22.1%	54.89%

TABLE 10 The CoE by considering the CO_2 mitigation cost-saving approach

	NPC($)	Initial capital cost ($)	O&M cost ($)	CoE (per Kwh)
Base case	8.74 M	159,743	663,689	0.469
Hybrid system	6.49 M	510,576	462,604	0.348

TABLE 11 Optimal design system compared with the base system

center in Deir al-Balah as a case study of our work since Gaza Strip has shortages in electric power and at the same time it faces COVID-19. Thus, providing a quarantine center with electricity is a challenging task. In this work, we present four HESs which are diesel electric generators only, wind/diesel electric generators HES, PV/diesel electric generators HES, and PV/wind/diesel electric generators HES. In the analysis, the fuel cost is considered equal to $1.47/l while looking for the optimal HES with minimum CoE. The results for different HES were given in Table 8. The result shows that the lowest CoE is $0.348/kWh in the case of PV/wind/diesel generators HES. When considering the cost of harmful emission, CoE for the systems were listed in Table 11 with a minimum CoE is $0.157/kWh for PV/wind/diesel generators HES. Fuel consumed and fuel cost of PV/wind/diesel electric generators HES is the lowest value. The simple payback interval is 1.88 years. Therefore, PV/wind/diesel generators HES are the most economical and environmentally friendly system.

AUTHOR CONTRIBUTIONS

Hala J. El-Khozondar: Conceptualization (lead); formal analysis (lead); methodology (supporting); software (equal); supervision (lead); writing – review and editing (lead). **Fady El-batta:** Formal analysis (equal); methodology (equal); software (equal); writing – original draft (supporting). **Rifa El-Khozondar:** Formal analysis (supporting); methodology (lead); software (supporting); writing – original draft (supporting). **Yasser Nassar:** Formal analysis (supporting); writing – review and editing (supporting). **Mansour Alranlawi:** Formal analysis (supporting); methodology (supporting). **Samer Alsadi:** Formal analysis (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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TABLE A1 The experiences of some countries in hybrid systems

Year	Publication	Country	Components	Load kWh/day- kWpeak	Grid	$/kWh
2015	Gan et al.[67]	Scotland	Wind/PV/diesel	15 kWh/day	Off-grid	0.78
2015	Diab et al.[68]	Egypt	PV/wind/diesel/battery	1100 kwh/day	Off-grid	0.19
2020	Alzaid et al.[69]	Saudi Arabia	Wind/PV	5 kW/h	Off-grid	0.33
2019	Major & Oshiemele[70]	Nigeria	Wind/diesel	50 MWpeak	Off-grid	0.077
2016	Ani[71]	Nigeria	PV/diesel	69 kWh/day.	Off-grid	0. 745
2019	Nurunnabi et al.[72]	Bangladesh	Wind/PV	2687.54 kwh/day	On-grid	0.097
2019	Nurunnabi et al.[72]	Bangladesh	Wind/PV	1521.37 kWh/day	Off-grid	0.288
2020	Rehman[73]	Saudi Arabia	PV/diesel	11,160 kWh/day	Off-grid	0.349
2015	El Khashab & Al Ghamedi[74]	Saudi Arabia	PV/wind/fuel cell	16 kWh/day	On-grid	0.36
2015	Jasim et al.[75]	Iraq	PV/diesel	76 kW peak	Off-grid	3.43
2019	El Attafi[76]	Morocco	PV/wind	3626 kW peak	Off-grid	0.130
2019	Ali and Jang[77]	South Korea	PV/Wind	7.296 MWh/yr	Off-grid	0.123
2015	Diab et al.[22]	Egypt	PV/wind/diesel/battery	10,000 kWh/day	Off-grid	0.17
2020	Costa & Villalva[78]	Brazil	PV/diesel	6.16 kWh/day 4.08 kWpeak	Off-grid	0.126
2021	Falama et al.[79]	Cameroon	PV/battery	12,231 Wh peak	On-grid	0.15
2018	Richa & Karaki[80]	Lebanon	PV/diesel	23 MWpeak/yr	Off-grid	0.0081
2021	Canziani et al.[81]	Peru	PV//diesel/battery	23 kWh	Off-grid	0.267
2013	Bahta[82]	Ethiopia	PV/wind/diesel/battery	1505 kWh/day	Off-grid	0.348
2016	Alayan[83]	Lebanon	PV/diesel	1775 kWh/day	On-grid	0.12
2021	Maoulida et al.[84]	Comoros	PV/wind/diesel	63 kWh/day	Off-grid	0.198
2016	Hassan et al.[85]	Iraq	PV/wind/diesel	93 kWh/day	Off-grid	0.321
2014	Nour & Rohani[86]	UAE	PV/diesel	24 MWh/day	Off-grid	0.313
2016	Sawle et al.[87]	China	PV/wind/diesel/battery	110.6 kWh/day	Off-grid	0.099
2021	Chauhan et al.[88]	India	PV/diesel/battery	89.80 kWpeak	Off-grid	0.261
2017	Rajbongshi et al.[89]	India	PV/biomass gasifier/diesel and grid	178 kWh/day	On-grid	0.91