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# Genetic algorithm based optimization on modeling and design of hybrid renewable energy systems

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ABSTRACT

A sizing optimization of a hybrid system consisting of photovoltaic (PV) panels, a backup source (microturbine or diesel), and a battery system minimizes the cost of energy production (COE), and a complete design of this optimized system supplying a small community with power in the Palestinian Territories is presented in this paper. A scenario that depends on a standalone PV, and another one that depends on a backup source alone were analyzed in this study. The optimization was achieved via the usage of genetic algorithm. The objective function minimizes the COE while covering the load demand with a specified value for the loss of load probability (LLP). The global warming emissions costs have been taken into account in this optimization analysis. Solar radiation data is firstly analyzed, and the tilt angle of the PV panels is then optimized. It was discovered that powering a small rural community using this hybrid system is cost-effective and extremely beneficial when compared to extending the utility grid to supply these remote areas, or just using conventional sources for this purpose. This hybrid system decreases both operating costs and the emission of pollutants. The hybrid system that realized these optimization purposes is the one constructed from a combination of these sources.


## 1. Introduction

Hybrid energy systems that depend on renewable energies, especially solar photovoltaic (PV), are nowadays in widespread usage. Their effectiveness was proven when they are used in supplying power to various locations, especially for small isolated loads. Their use can mitigate the effects of greenhouse gases to meet the requirements of the Kyoto protocol, as they mainly reduce $CO_2$, NO, $NO_2$, and $SO_2$ emissions where other emissions are also subject to reduction. Their low maintenance costs and low pollutant emissions are regarded as its main advantages [1–8].

This paper addresses an approach based on genetic algorithm in designing a hybrid system with solar PV as a renewable source, and microturbine or a diesel generator as its backup source. The study has been carried out for a Mediterranean climate, particularly Palestine. Fig. 1 illustrates the block diagram of the proposed hybrid energy system. The DC bus and the AC bus are linked via the bidirectional inverter where the DC bus combines both the DC output of the PV panels through the solar charger converter and the battery bank, whereas the AC bus combines both the output of the microturbine and the load.

Using systems with more than one supply source; known as hybrid systems to supply power to a certain application can increase reliability and energy security compared to systems with only a single energy source [9–12].

The hybrid system types mainly depend on the renewable energy source and its availability. In Palestine, solar radiation has high potentials with high values for annual sunshine hours. Average values of between 5.5 kW h/m$^2$ and 6 kW h/m$^2$ on a horizontal surface have been recorded for the annual average daily solar radiations [13].

In the Palestinian Territories, there are many small communities in remote and isolated areas. These communities depend on diesel generators for their home electrical supply. Moreover, the Palestinian Territories depend on external power sources,

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**Nomenclature**

| | |
|---|---|
| $a$ | ideality factor |
| $COE$ | cost of energy (\$/kW h) |
| $DPR$ | degradation percentage rate |
| $E_{MT_E}(h)$ | electrical energy generated by microturbine at hour $h$ (kW h) |
| $E_{MT_H}(h)$ | heat energy generated by microturbine at hour $h$ (kW h) |
| $E_{PV}(h)$ | energy generated by PV system at hour $h$ (kW h) |
| $FF_{MT}$ | microturbine fuel consumption rate ($m^3$/h) |
| $G$ | solar radiation intensity (W/$m^2$) |
| $G_{STC}$ | solar radiation intensity at standard test conditions ($G_{STC}$ = 1000 W/$m^2$) |
| $h$ | height over sea level (m) |
| $I_0$ | diode saturation current |
| $I_{mp\text{-}STC}$ | maximum power point PV current at standard test conditions |
| $I_{Ph}$ | photon current |
| $I_{PV}$ | PV output current |
| $K_T$ | power temperature coefficient ($K_T = -3.7 \times 10^{-3}$ (1/°C)) for both mono and multi crystalline Si) |
| LLP | loss of load probability |
| $P_{mp\text{-}STC}$ | PV rated power at standard test conditions |
| $P_{MT\text{-}mod}$ | microturbine output power (kW) |
| $P_{MT\text{-}rat}$ | microturbine rated power (kW) |
| $P_{PV\text{-}gen}$ | PV module generated power (W) |
| $P_{pv\ sysm\_(n)}$ | PV system size at year n (kW) |
| $R_P$ | shunt resistance in the equivalent circuit of the PV module |
| $R_S$ | series resistance in the equivalent circuit of the PV module |
| SOC | battery state of charge |
| $T_{amb}$ | ambient temperature (°C) |
| $V_{PV}$ | PV output voltage |
| $V_T$ | thermal voltage |

with limitations on the available capacity required. As a result of this, more than 30% of the Palestinian households receive an interrupted power supply [14]. Supplying these remote locations and working to solve the power supply shortage problems are the main priorities of different institutions in Palestine. Small projects using PV/diesel generator hybrid systems have been implemented to supply power to parts of these small communities. Microturbines possess a number of attractive features compared to diesel generators, such as lower operational costs and maintenance, higher levels of reliability, lesser noise and pollutant emissions, and more fuel flexibility [9]. These features render the usage of microturbines as standby sources more attractive compared to diesel generators.

Sizing optimization of the hybrid system components to minimize the cost of energy production, as well as maximizing utilization of solar panels and minimizing the pollutant emissions forms the main objectives of this study.

Balancing energy for each hour throughout the entire year is a step that should be taken before running or while performing the optimization. For this purpose, the energy generated by each energy source should be calculated. This requires mathematical modeling of each component in the system that in turn requires the availability of climate data, which necessitates the analysis of these data.

The solar radiation analysis and developing a mathematical model of the components making up the hybrid system are essential steps that need to be completed prior to carrying out the sizing optimization of the hybrid system components, which will be presented at the end of this study. In [13,15], suitable approaches have been developed to analyze solar radiation, calculating the optimized tilt and surface azimuth angles, predicting solar radiation, and mathematically model the solar panels. These developed approaches will be used in this study.

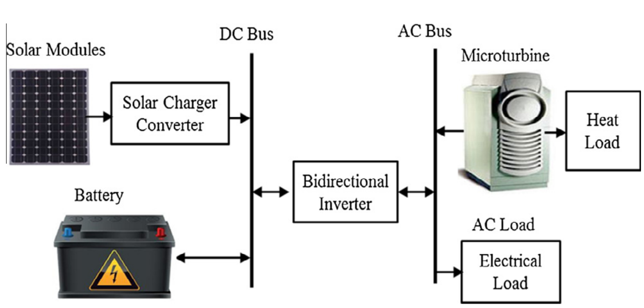


**Fig. 1.** Block diagram of the suggested hybrid system.

While iterative or graphical techniques have been recommended and used for the purpose of optimization of hybrid system components by many researchers, the novel algorithms have been utilized for this purpose by a lesser number of researchers. In novel approaches, a design space of possible solutions for the optimum sizes of the components is firstly constructed. A searching method is then used to select the most optimal configuration satisfying the stated objective functions. These approaches are recommended when the multi-objective function has to be satisfied, and/or when various parameters (variables) constructing the decision vector need to be optimized. They are also recommended when the operating strategy of the hybrid system has to be optimized as well. In reality, it is difficult to use linear programming or iterative approaches to solve such optimization problems. Genetic algorithm, particle swarm optimization, and simulated annealing approach are examples of these novel searching-techniques. Other less common approaches may be found in the literature. Each of these approaches has its own features, but a review of the literature indicates that the genetic algorithm possess superior features that makes it common for optimization purposes, especially for hybrid systems. Its performance for searching the global optimum is extremely efficient, and is very suitable for optimization problems of a great number of optimized parameters. In comparison with other algorithms, it is relatively harder to code, and requires more computation time to solve the optimization problems [16].

Koutroulis et al. [17] used genetic algorithm to optimize the sizes of the components making up a standalone hybrid energy system constructed of PV panels, wind turbines, and a battery bank. In this study, the type and the number of each component have been optimized, realizing minimum cost while covering the load requirement with zero load rejection. The simulation results showed the effectiveness of using genetic algorithm for the purpose of optimization. In another study, genetic algorithm was used by Hongxing et al. [18] to optimize the number of components needed to construct a wind/solar with a battery-hybrid system. The installation height of the wind turbine and the tilt angle of the PV panels were optimized as well. Minimizing the COE at a specified value of loss of power supply probability was the objective function for this optimization. The load in this study was a telecommunication relay station, and a pilot system was built based on the optimization results. In another study, Dufo-Lopez and Bernal-Agustin [19] developed a software program that uses genetic algorithm to design a PV–diesel hybrid system. The simulation results of the system optimized in this study were compared with a similar system designed using classical methods. The computational results showed the economic advantages of using novel algorithms to solve such optimization problems. Rajkumar et al. [20] proposed an optimization methodology for a PV/wind/battery hybrid system. According to their methodology, an adaptive neuro-fuzzy inference system was used to develop a model for both the PV and the wind sources by predicting their output(s). This prediction is based on training the model using various acquired weather data and the corresponding generated powers by specified types of components. According to their approach, an iterative method was used to find the configuration of the hybrid system with the lowest cost and excess energy. They depended on Malaysian metrological data to conduct their study, and their results showed that the developed model was able to produce accurate values for the output power. Furthermore, the selected configuration had the ability to meet the load requirement at the minimum cost and excess energy. The results of this approach cannot be generalized, since specific types of components were used for training purposes.

A microturbine/wind turbine hybrid system was studied and analyzed by Caisheng et al. [21]. The effectiveness of using such hybrid systems to supply residential loads has been proven, where the operation of the wind turbine was integrated with the operation of the microturbine to maintain high levels of reliability. An iterative approach was to analyze a hybrid system composed of PV and a microturbine as a backup source [22]. In this study, the optimization parameters were only the size of both the PV panels and the battery bank. A comparison between using microturbine as a backup source and the usage of other types of backup sources was not included in this study. Furthermore, the modeling of the PV system was accomplished by using basic equations. Although these equations have been used by many researchers with their effectiveness being approved of in modeling the PV system, accounting for the effect of the series and shunt resistances of the equivalent circuit, as well as the ideality factor will surely increase the accuracy of the model. Mohamed and Koivo [8] proposed an approach using genetic algorithm to determine the optimal operating strategy for a microgrid, consisting of wind turbine, PV array, diesel generator, microturbine, fuel cells, and storage battery. The load being considered was a residential application. The sources capacities in this study were assumed to be constant, and the implemented genetic algorithm was to define the optimal settings of these different sources for the purpose of minimizing the cost function. The study presented the results of the simulation, while the typical values of the capacities of different components, the different costs, and the constraints used to obtain these results were not included.

Despite considerable work being carried out by the previously mentioned studies and many others on the optimization of hybrid systems, none of them have analyzed the hybrid systems with microturbines as backup sources or accounting for the cogeneration feature of the microturbines to the best of the authors' knowledge. Part of the previously reviewed studies used genetic algorithm to optimize renewable hybrid systems with or without diesel generators as backup sources. The others used genetic algorithm to determine the optimal operating strategy of a microgrid consisting of various sources with microturbine was one where the size of the components were assumed to be constant in these studies. Furthermore, and as previously mentioned, in these studies, the electrical output of the microturbine was accounted for without utilizing the cogeneration feature of the microturbine.

In this paper, genetic algorithm has been used to optimize the sizes of the various components of the hybrid system, where types (brand names) of these components have been selected from various assigned types, and the objective function is to minimize the COE. The optimized parameters also include the PV tilt and surface azimuth angles. A possibility in optimizing the type of each of the components is also involved here. In this case, the type of the PV mounting structure is also optimized. Comparison of the results of this hybrid system with the hybrid system where a diesel generator is used as a backup source instead of a microturbine is also conducted. The effect on the COE, taking into account the case where the load is covered with 100% reliability and the case where a certain value for LLP is specified, has been studied as well.

## 2. System modeling

### 2.1. Components modeling

In this study, the PV module tilt angle is optimized by maximizing the annual energy production. For this purpose, the measured solar radiation data on a horizontal surface are used to calculate the radiation data on a tilted surface. The adopted model used for this calculation is the anisotropic model, while the correlation selected to calculate the diffused component of the solar radiation is the Orgill and Holand correlations. This approach is usually recommended, especially for the surfaces oriented toward the equator [23]. Ref. [23] also includes all the equations and models used for this calculation. Genetic algorithm has been used to carry out this tilt angle optimization, where a 1 kWp of PV panels was selected to calculate their annual energy production. The objective function is to maximize the annual energy production of the PV panels. The hourly data for both solar radiation and temperatures (for Nablus site) were used. The lower and upper constraints of the optimized tilt angle were 0° and 90°, respectively.

To calculate the PV generated energy, a mathematical model of the PV panel that accurately describes its operation, and took into account the effect of variation of both the solar radiation and temperatures should be developed and used. Humidity, wind velocity and other climatic indicators also have an effect on the operation of the PV panels and on their ability to generate power. Their effect is usually indirect, so it is not directly included in the mathematical model of the PV panel itself but taken into account in the techno economic analysis. The effect of water vapor particles on the sunlight irradiance level, the effect of humidity on the dust accumulation on the PV surfaces, and the effect of humidity on the solar cell encapsulate materials should be considered. The first effect has been considered as it affects the solar radiation and the solar radiation variation is already considered in the model. The cost of regular cleaning of the surfaces of the PV panels to remove any accumulated dust is included in the annual maintenance cost of the PV system, so the second effect is already considered in the analysis. The performance degradation of the PV panels due to exposing them to high humidity for long periods of time in addition to other factors causing this degradation has also been taken into account in the analysis as it will be discussed later in this section. The PV model parameters such as the series resistance ($R_S$), the shunt resistance ($R_P$), and the diode ideality factor ($a$) should be calculated using one of the various available approaches in order for them to be used in the model to determine the energy. A mathematical model based on a single-diode or two-diode models can be used for this purpose. In the case where the parameters of the PV model are available or calculated, Eq. (1) can be used to calculate the PV generated power. In this equation, both the PV panel voltage and current should be known, but as they are interdependent, a numerical approach should be used to calculate the PV panel output voltage if the output current $I_{PV}(G,T)$ is known. The PV output current can be calculated using (2), where $I_{mp\text{-}STC}$ is the maximum power point current at standard test conditions (given by manufacturer). This equation can be satisfactorily used for this purpose, as most of the solar regulators usually include the maximum power point tracker circuit that maintains the working state of the PV output remaining around the maximum power point.

$$P_{PV\text{-}gen} = V_{PV} * I_{Ph} - V_{PV} * I_0 \left[ \exp\left( \frac{V_{PV} + I_{PV} * R_S}{a * V_T} \right) - 1 \right] - V_{PV} * \left( \frac{V_{PV} + I_{PV} * R_S}{R_P} \right) \quad (1)$$

$$I_{PV}(G,T) = I_{mp\text{-}STC} * (G/G_{STC}) \quad (2)$$

In (2), $G$ (W/m$^2$) is the radiation calculated on the tilted surface, while $G_{STC}$ is the standard test solar radiation. It is equal to 1000 W/m$^2$.

In this paper, genetic algorithm has been used to compute values of the PV model parameters that suit the whole range of the solar radiation and the wide range of temperatures. For this calculation, the decision vector includes the three aforementioned PV model parameters, but according to the equivalent circuit used to describe the PV model, it can include additional parameters, such as saturation current and/or photon current. In the two-diode model, the ideality factor and the saturation current of the second diode can also be included within the parameters of the decision vector. Ref. [15] tested the various alternatives (single diode or two diodes with or without saturation current and photon current), and recommended a 3-parameters single-diode model due to the fact that it demonstrated the most accurate results.

The lower and upper constraints of the diode ideality constant are 1 and 2, respectively. For the series resistance, the lower and upper constraints are 0.01 Ω and 1.2 Ω, respectively, while the lower and upper constraints of the shunt resistance are 50 Ω and 1000 Ω, respectively.

For brevity, equations to calculate the photon current ($I_{Ph}$), the diode saturation current ($I_0$), and the thermal voltage ($V_T$) are not included here. Equations that take into account solar radiation and temperature effects to calculate them are detailed in [15].

The PV system annual performance degrades by a certain percentage. This degradation in performance is mainly due to the cell and module internal interconnections, outside moisture, and the materials used in the packaging process. The type of the PV panels and their respective manufacturers are the main factors influencing the value of this degradation. A typical value of 1% has been suggested by Bortolini et al. [24] for this degradation rate. Any mismatch losses can be considered within this degradation rate. These mismatch losses express the difference between the maximum power of the array as a whole set, and the sum of the maximum powers of each panel. Part of these losses is due to the previously mentioned manufacturing defects, while the rest is due to the fact that a dispersion of the electrical characteristics of the modules usually occurs when the PV array is composed of more than one string [25]. One of the approaches that may be followed to account for this degradation is by compensating its effect with annual increments of the PV system's size by a percentage that equals to the percentage assigned for the degradation of the percentage rate. This way, the size of the PV system at year $n$ ($P_{pv\ sysm\_(n)}$) is equal to the size of the PV system at year $n-1$ ($P_{pv\ sysm\_(n-1)}$), added to the size of the PV system at year $n-1$, multiplied by the degradation percentage rate ($DPR$):

$$P_{pv\,sysm\_(n)} = P_{pv\,sysm\_(n-1)} + DPR \times P_{pv\,sysm\_(n-1)}; \quad n = 2, 3, 4, \ldots, \text{ lifetime of the project} \quad (3)$$

For the other components making up the hybrid system: the battery bank, the charge regulator, diesel generator fuel consumption, and the bidirectional inverter, refs. [3,18,26] include detailed description regarding their respective roles and models.

The microturbine fuel consumption at certain interval depends on the actual generated power at this interval. The microturbine manufacturer usually gives in a table or a plot data regarding the natural gas flow as a fuel of the microturbine for different values of loads. For a 30-kW Capstone microturbine, a first order relation between the natural gas flow ($FF_{MT}$) in (m$^3$/h), and the microturbine output power ($P_{MT\text{-}mod}$) in (kW) is given in (4). This equation is developed based on a table given in [27] that links the natural gas fuel consumption and the microturbine output power.

$$FF_{MT} = 0.314(P_{MT\text{-}mod}) + 1.548 \quad (4)$$

The modified output power of the microturbine is the output power of the microturbine after taking into account the effect of ambient and the altitude over sea level on the amount of power generated by the microturbine. Eq. (5) provides the relation that accounts for these effects. This equation is developed based on the graphs provided in [27]. The first graph links the microturbine output power and the ambient temperature, while the second one links the microturbine output power to the height over sea level.

$$P_{MT\text{-}mod} = P_{MT\text{-}rat} * (1 - 0.0001 * h) * (0.911 - 0.005 * T_{amb}) \quad (5)$$

where $P_{MT\text{-}rat}$ is the rated power of the microturbine, $h$ is the height in (m) over sea level, and $T_{amb}$ in (°C) is the ambient temperature.

### 2.2. Economical modeling

Different types of costs should be taken into account when conducting economic analysis. These costs include the capital costs of various components and their installation costs, operation and maintenance costs, and replacement costs. The salvage value and the value of money are taken into account as well. The economic analysis in this paper utilizes life cycle costing. This is essential when trying to compare the different scenarios being analyzed in order to allow for the selection of the least costly option. For comparison purposes, the cost of production of one unit of energy (COE) is calculated for each scenario.

The economic analysis also requires the definition of the life cycle time of the project, as well as the lifetime of different components making up the system. The component with the maximum lifetime from various components making up any project usually specifies the life cycle time of this project. For the hybrid system considered in this paper, the maximum lifetime is for the PV panels, equaling 25 years. For any microturbine, the manufacturer usually specifies the time (in operating hours) prior to overhaul, and the time (also in operating hours) prior to replacement of the microturbine. The lifetime of the battery system is mainly dependent on the number of cycles of discharge/charge of the battery, and the value of the depth of discharge.

## 3. Simulation approach and optimal sizing procedure

### 3.1. Simulation approach

For each hour in the year, energy is balanced, and for this purpose, a simulation program was developed. The purpose of this program is to simulate the operation of a hybrid system that includes more than one energy source according to the strategy specified for the management of the power flow via this hybrid system. The power flow between the different sources in the hybrid system and the priorities that determine this power flow are specified according to this strategy. This strategy is based on maximizing the utilization of the PV system, so the energy generated by the PV panels and stored in the battery bank has the priority to supply the load. If this energy does not cover the load requirement, a decision to run the microturbine as a standby source should be taken.

In certain cases where the energy generated by the PV panels exceeds the load requirement and the batteries are fully charged, a dump load is used to consume this excess energy. As previously mentioned, a decision to operate the microturbine is taken when the battery bank is discharged to its maximum allowable depth of discharge level and there is no sufficient generated energy by PV system to supply the load. This case continues until the battery is fully recharged, where the bidirectional inverter works as a rectifier and permits charging the battery.

The energy balance conducted in this study is based on the assumption that no power interruption occurs throughout the year (zero not served load energy), or on the assumption that a certain value for LLP is allowed. The value of LLP is calculated using the following equation:

$$\text{LLP} = \frac{\sum_{h=1}^{h=8760} \text{Energy deficit } (h)}{\sum_{h=1}^{h=8760} \text{Load demand } (h)} \tag{6}$$

where Energy deficit ($h$) is the amount of energy required by the load at a certain hour, but cannot be covered by the various generation or storage sources. It can be calculated using the following formula:

$$\text{Energy deficit } (h) = \text{Load demand } (h) - [E_{PV}(h) + E_{MT_E}(h) + E_{MT_H}(h)E_B(h-1)] \tag{7}$$

where $E_{PV}(h)$ is the energy generated by the PV panels at a certain hour, $E_{MT_E}(h)$ is the electrical energy generated by the microturbine at certain hour, $E_{MT_H}(h)$ is the heat energy generated by the microturbine and directly utilized by the heat load, and $E_B(h-1)$ is the energy stored in the battery at the end of the previous hour.

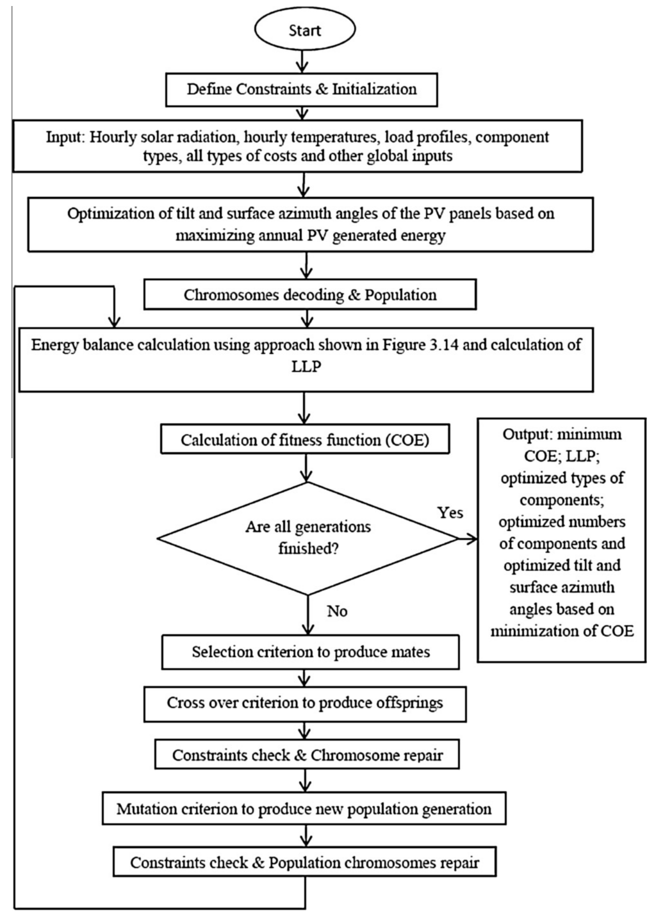


**Fig. 2.** Flowchart of the genetic algorithm.

*3.2. Components sizing optimization based on genetic algorithm*

The genetic algorithm is one of the novel algorithms that can be used to solve optimization problems in different aspects of life. The individual solutions constituting the population are randomly selected at each step. There are three main rules used by genetic algorithm to form the next generation from the current population; selection rules, crossover rules, and mutation rules [28].

As earlier mentioned, the purpose of optimization is to select the sizes of components making up the hybrid system in order to satisfy the various predetermined objective functions. Genetic algorithm has been utilized to conduct this optimization problem and for this purpose a MATLAB code has been developed. This code includes both the genetic algorithm programming and the programming of the optimization fitness function. In this code, the initial population generation is formed by randomly generating population members (possible solutions). Each possible solution is a code of the decision vector, taking into account the upper and lower constraints. This initial generation evolves through successive iterations, and members of each generation are evaluated in order to calculate the fitness function (the COE), with the member possessing the minimum COE being selected. Fig. 2 shows the flowchart upon which the genetic algorithm performs the optimization process.

In this method, and after performing many executions, it was discovered that a population size of 50 is adequate for the purpose of this optimization, while the number of generations required to give the most optimal solution is 80. In most cases, the number of required generations is less than 60. The crossover factor was selected to be 0.8, whereas the mutation factor was selected to be 0.2. The selection function was the Roulette and the crossover function was the arithmetic one. The mutation function was selected to be the Gaussian one and the stopping criteria is the number of specified generations. Actually, other function types can be satisfactorily used and this depends on the optimization problem itself. Whether the problem is constrained or not and the number of parameters to be optimized are within the factors that specify the functions to be used. For the same optimization problem considered in this study but using the MATLAB optimization Toolbox, different functions were tested. It was found that the functions that gave accurate results with less number of generations are the functions that were previously specified. More discussion about these specified functions and others can be found in Help menu of the MATLAB optimization Toolbox.

For each generation, the value of LLP is calculated for each population member. The member that does not fulfil the load requirement at a certain value for LLP is excluded from the population. The crossover, mating and mutation processes are performed on the successful members only. After finishing the mutation process, any excluded member is substituted by another one in such a way to maintain the size of the population the same at the beginning of each generation. The process continues until all generations (iterations) are finished or the stopping criterion is satisfied. In each iteration, the member that possesses the minimum COE will be selected.

The parameters constructing the decision vector being optimized are: type of the PV panel ($T_{PV}$), type of the battery ($T_B$), type of the microturbine ($T_{MT}$), type of the PV mounting fixture ($T_F$), number of PV panels ($N_{PV}$), number of battery units ($N_B$), number of microturbines ($N_{MT}$), tilt angle ($\beta$) of the PV panels based on minimizing COE, and PV panels surface azimuth angle ($\gamma$) based on minimizing COE. In the case of specifying the types, the parameters being optimized are just the numbers of each component. Generally, the decision vector (*DV*) is given in the following equation:

$$DV = \lfloor T_{PV}, T_B, T_{MT}, T_F, N_{PV}, N_B, N_{MT}, \beta, \gamma \rfloor \quad (8)$$

The objective function being optimized is the COE. The purpose is to minimize this fitness function. As previously mentioned, the COE is the cost of generating 1 kW h of energy utilized by the load, and can be calculated as follows:

$$COE = \frac{TAC}{TALE} \quad (9)$$

where *TAC* is the total annual cost, and *TALE* is the total annual load energy. When calculating *TAC*, various types of costs for various components constructing the hybrid system should be considered. The different types of costs were previously mentioned. Furthermore, costs of gaseous emissions, mainly $CO_2$, NOx, and SOx were included in the calculation of *TAC*. Tables 1–4 included in the following subsection display the different types of costs associated with different components.

The lower and upper constraints for different parameters that should be taken into account while solving this genetic algorithm optimized function depend on the parameter itself. For the type, the lower constraint should be greater than or equal to zero and the upper constraint is the number of available types for optimization process, while for the number, the lower constraint should be greater than or equal to zero, and theoretically, no limitation should be imposed on the upper constraint.

### 3.3. Simulation inputs

The remote small communities that planned to be supplied by these suggested hybrid systems are located in different locations throughout the Palestinian Territories. Number of them is located in Ramallah region. For the purpose of specifying the load curve for one of these remote communities that located in Ramallah region (31.8°N latitude; 35.23°E longitude), a neighbor electrified community was chosen. The measurements and the questionnaire were carried out in this community. It was expected that this community might have the same consumption behavior as the neighbor un-electrified community.

In the Palestinian Territories, the climate is a seasonal climate, so the load consumption differs from season to season. Two categories for this load consumption were considered. One of these categories was for the summer (hot) period, whereas the other was for the winter (cold) period. For each category, a workday and a weekend day were also considered. The measurements of the total load for both of these categories were done for a whole week and hourly average values have been obtained. The heat part of the load was estimated for the two categories after analyzing the results of a questionnaire developed for this purpose. The questionnaire included number of questions that helped in forming the heat load profile. The questions tried to determine the type of the heat load that operated during each hour in this community. So, the heat load that can be supplied directly by the microturbine was specified. Fig. 3 shows the hourly load profile for the different mentioned categories and for both the total load and the heat load.

As mentioned earlier, both hourly solar radiation and ambient temperatures are required to calculate the PV panels generated power. For locations under consideration, it has been found that the yearly average daily solar radiation on a horizontal surface is 5.94 kW h/m$^2$/day, while the sunshine hours exceed 3000 h per year.

For the optimization purposes in this paper, 4 types of PV panels, 4 types of battery units, 2 types of mounting fixtures, and 2 types of microturbines were selected from different manufacturers. As previously mentioned, assigning a type while optimizing the number of units from this type, or optimizing both the type and the number are the possibilities available in this study. Ratings and various costs of the selected types of the battery units [29], PV panels [29], and microturbines [27] are included in Tables 1–3, respectively. Other inputs required by the simulation program are displayed in Table 4. The amount (in kg/MW h) of $CO_2$, NOx, and SOx gas emissions generated by the microturbine and the diesel generator, and the cost (in $/kg) of each of these emissions are also included in this table [27].

The first type of the mounting fixtures is the one that may be fixed onto a roof or ground, with the possibility to incline it at a certain tilt angle, while the second type is a single-axis tracker that has the ability to closely follow the sun's movements. This single-axis fixture moves in such a way that it maintains the surface azimuth angle of the panels to be equal to the solar azimuth angle. The number of panels that can be supported by each mounting type depends on mounting type itself, as well as the panels' type.

### 3.4. Development of optimization software

For the purpose of analysis and optimization of hybrid renewable energy systems in this paper, a MATLAB-based software has been developed. This software is used to optimize the off-grid hybrid system that is based on PV as a renewable source. The optimization performed in this software includes the tilt angle optimization, the components sizes optimization, as well as the type (brand name) of these components. The type of the mounting fixture of the PV panels falls within the optimized parameters.

Many commercial software tools have been developed for simulation and optimization of hybrid renewable energy systems. The following are some of the major and most common software packages that have been used to optimize hybrid renewable systems: RETScreen, SolarDesignTool, SolarPro, PVSYST 4.33, and HOMER. Each of these software tools has their respective features and capabilities in simulating and optimizing hybrid systems. Lalwani et al. [30] reviewed these software tools and others in great detail in order to address the features and the purported applications of each of them. O top of this review, Khatib et al. [31] compared between parts these software tools in terms of their applications and simulation capabilities. One of the most widely used software packages is the HOMER. This software has the capability to simulate various types of PV systems; furthermore, it can perform optimization and sensitivity analysis.

While HOMER or other simulation and optimization packages can be very useful, the developed software in this paper can be adapted to deal with different cases, to calculate different parameters, and analyze the effect of the alteration of any parameter upon the results. The mathematical models used to characterize the various components are selected to account for the different real-world conditions affecting the operation of each of these components. For example, in the developed software, the way

**Table 1**
Specifications of various types of batteries used in the analysis.

| | Battery type | | | |
|---|---|---|---|---|
| | Type1 | Type2 | Type3 | Type4 |
| Battery capacity (A h) | 2430 | 1700 | 1215 | 648 |
| Battery voltage (V) | 2 | 2 | 2 | 2 |
| Battery cost ($/unit) | 1271 | 836 | 609 | 305 |
| Battery maintenance cost ($/unit/year) | 15 | 11 | 8 | 4 |

**Table 2**
Specifications of various types of PV panels and the corresponding mounting fixtures used in the analysis.

| | PV type | | | |
|---|---|---|---|---|
| | Type1 | Type2 | Type3 | Type4 |
| Rating (W) | 135 | 175 | 220 | 235 |
| Cost ($/W) | 2.27 | 1.37 | 1.54 | 1.18 |
| Installation cost ($/W) | 0.7 | 0.7 | 0.7 | 0.7 |
| Maintenance cost ($/W/year) | 0.025 | 0.025 | 0.025 | 0.025 |
| No PV panels per mounting structure of type1 | 2 | 2 | 2 | 2 |
| No PV panels per mounting structure of type2 | 11 | 12 | 9 | 9 |
| Cost of mounting structure of type1 ($/unit) | 263 | 289 | 397 | 397 |
| Cost of mounting structure of type2 ($/unit) | 2452 | 3636 | 3636 | 3636 |

**Table 3**
Specifications of the two microturbine types used in the analysis.

| | Microturbine type | |
|---|---|---|
| | Type1 | Type2 |
| Rating (kW) | 30 | 65 |
| Capital cost ($/kW) | 2970 | 2490 |
| Maintenance cost ($/kW h/year)[a] | 0.02 | 0.0175 |

[a] It includes replacement and inspection of components and the cost of the major overhaul (this is included in a service contract).

**Table 4**
Other simulation program inputs.

| Item | Value |
|---|---|
| Capital cost of the bi-directional inverter ($/kW) | 715.0 |
| Capital cost of the PV solar charger converter ($/kW) | 450.0 |
| Capital cost of the diesel generator ($/kW) | 550.0 |
| Efficiency of the bi-directional inverter (%) | 92.0 |
| Efficiency of the PV solar charger converter (%) | 95.0 |
| W h efficiency of the battery units (%) | 85.0 |
| Lifetime of the PV panels (year) | 25.0 |
| Lifetime of the battery units (year) | 6.0 |
| Lifetime of the project (year) | 25.0 |
| Fuel price of natural gas ($/m$^3$) | 0.33 |
| Diesel price ($/l) | 1.77 |
| Replacement time of fuel and air filters (h) | 8,000 |
| Replacement time of thermocouples, igniters and fuel injectors (h) | 16,000–20,000 |
| Replacement time of the microturbine battery (h) | 20,000 |
| Time to major overhaul (includes replacement of core turbine) (h) | 40,000 |
| Replacement time of the microturbine (h) | 80,000 |
| Replacement time of diesel engine (h) | 24,000 |
| Rate of interest (discount) (%) | 8.0 |
| Rate of general inflation (%) | 4.0 |
| Rate of fuel inflation (%) | 5.0 |
| $CO_2$ emissions of the microturbine (kg/MW h) | 787.4 |
| NOx emissions of the microturbine (kg/MW h) | 0.245 |
| SOx emissions of the microturbine (kg/MW h) | 0.008 |
| $CO_2$ emissions of the diesel generator (kg/MW h) | 649.5 |
| NOx emissions of the diesel generator (kg/MW h) | 9.89 |
| SOx emissions of the diesel generator (kg/MW h) | 0.206 |
| Cost of $CO_2$ ($/kg) | 0.014 |
| Cost of NOx ($/kg) | 4.2 |
| Cost of SOx ($/kg) | 0.99 |

the generated power of the PV panels is calculated, the way the PV tilt and surface azimuth angles are specified, and the way the degradation (derating) of the PV panels is considered differs from HOMER. Another example is the modeling of the fuel consumption of the microturbine, where the effect of the ambient temperature and the effect of the height over the sea level of the site are considered in the developed model, while they cannot be considered in the fuel consumption modeling of the generator in HOMER. The possibility to optimize the type of the component alongside the size of the component, the possibility to optimize the type of the tracking system, the possibility to include the tilt and the surface azimuth angles in the optimization, the ability to predict the solar radiation data in the locations without measurements of this quantity but with sunshine hours measurements are some of the features present in this developed software that is not in others.

Furthermore, the developed software helps to find and calculate hourly, daily, monthly, or yearly results. For some cases, the code of the software can be adapted to find – for example – the hours in the year that the system is not able to meet the load demand. Any variable can be plotted to demonstrate the results in a more obvious manner. It provides more flexibility, as it can be adapted to deal with any new cases that may arise. In most of ready software packages, the user has to use the models adopted by the developers of these packages, as these packages introduce black boxes to represent the various components.

## 4. Results and discussion

### *4.1. Results of PV panels mathematical modeling*

The approach used to model the PV panels depends on the extraction of the parameters using genetic algorithm. Table 5 illustrates the values of the 3 parameters used in the model for each type of the PV panels mentioned in Table 2. The percentage values of the average absolute errors in currents are calculated based on referring them to the corresponding current at the maximum power point. The calculated error is the difference between the PV outputs current calculated using the extracted values of the parameters and the current provided by the manufacturer.

### *4.2. Results of solar data analysis (panel angles optimization)*

Genetic algorithm has been used to optimize both the PV tilt and surface azimuth angles. A value of 32.8° was obtained for the PV tilt angle when optimized on the basis of maximizing the annual PV energy production. The PV panels surface azimuth angle was optimized as well. While directing the PV panels directly toward the south in the northern hemisphere is usually done, directing them with a certain angle towards the east or the west of the south may result in greater annual energy productions. In this study, an optimum value for this angle was found to be +16° (i.e. west of due south). The fact that the optimum surface azimuth angle is taken into consideration when maximizing the annual energy production of the PV panels might be dissimilar to the optimum angle being taken into consideration when minimizing the COE is prominent here.

### *4.3. Results of hybrid system sizing optimization*

In this paper, different scenarios and cases have been analyzed to select the most optimal configuration that covers the load demand with the specified value of LLP, with minimum COE

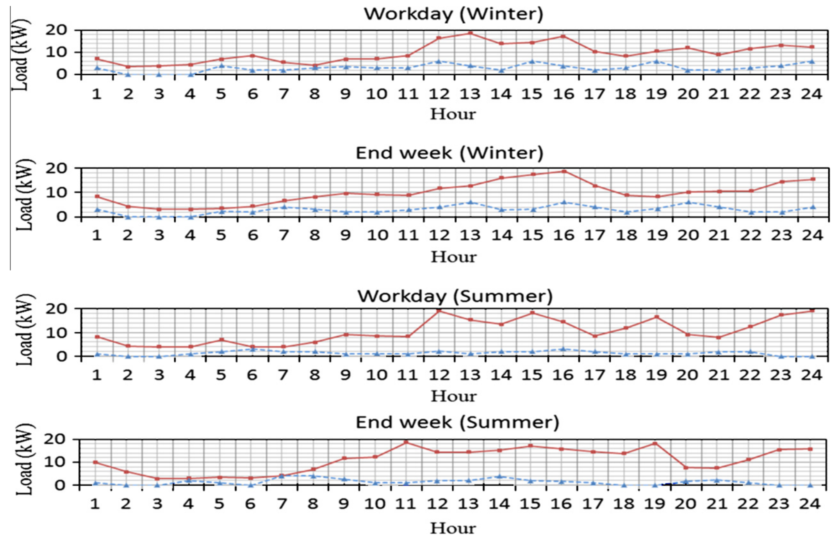


**Fig. 3.** Hourly typical load profiles (solid red for total load and dashed blue for heat load). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 5**
PV model parameters (extracted using genetic algorithm).

| Parameter | PV type | | | |
|---|---|---|---|---|
| | Type1 | Type2 | Type3 | Type4 |
| Ideality factor (a) | 1.175 | 1.014 | 1.08 | 1.037 |
| Series resistance ($R_S$) in Ω | 0.228 | 0.715 | 0.371 | 0.338 |
| Shunt resistance ($R_P$) in Ω | 921.9 | 987.6 | 972.6 | 935.9 |
| Percentage of average absolute error in current (%) | 0.18 | 0.25 | 0.19 | 0.19 |

production. Table 6 displays the results of some selected cases of the hybrid system.

*4.3.1. Results of the best optimized case*

*Case 1 (the best optimized case)*: Optimization of both the component type and the corresponding number from each type. For this case, the tilt and the surface azimuth angles are the ones being optimized, minimizing the COE rather than the angles optimized on the basis of maximizing the annual PV energy production. From the previous subsection, the optimized tilt angle that maximizes the energy produced by the PV panels was determined to be 32.8°, while the optimized surface azimuth angle that maximizes the energy production is 16°. This ensures that the optimized tilt angle or surface azimuth angle that maximizes the annual energy production does not mean the same optimized angle will minimize the COE. In fact, the difference is so small between the values of COE accounting for the optimized tilt and surface azimuth angles accounting for the minimization of the COE, and the COE accounting for both optimized tilt and surface azimuth angles, taking into account the maximization of the annual energy production.

In this case, the microturbine works in its cogeneration mode, where the heat load is directly supplied by the heat energy generated during the operation of microturbine (via a heat exchanger), while the microturbine electrical output provides only the electrical load. In this case, the microturbine works at its rated power to provide the electrical load, and the surplus generated power is utilized to charge the battery through a bidirectional inverter. The case where the microturbine electrical output supplies both the electrical and the heat loads is numbered case 14, while the case where the microturbine works to follow the load changes is numbered case 15. In this case, no surplus power is available to charge the batteries.

As displayed in Table 5, the microturbine annually runs for about 2692 h. This means that it operates every day for a certain number of hours. The simulation results indicate that the microturbine-generated energy is about 57% of the total generated energy by the microturbine itself and the PV panels. The simulation results also indicate that 4% of the total generated energy has been dumped, while the total energy lost on an annual basis is about 14%. This means that the energy efficiency of this hybrid system is about 86%.

The microturbine capital cost is considered the highest amongst the other components' capital costs. It is about 49% of the total initial costs, while it is about 41% of the total initial costs for the PV system, which includes, in addition to the PV panels, the PV regulator and the battery bank. The rest of the cost goes to the bidirectional inverter. The energy contributed by the microturbine and the PV system for each month is shown in Fig. 4. The monthly load and dump energies are also shown in the same figure. It is noticeable that the energy generated by the microturbine is higher in the months of lower PV energy. Within these months, the dump energy is also higher. This is due to the fact that the microturbine is running at its rated power, while the utilized heat that is generated from the microturbine through the heat exchanger directly supplies the load heat energy. In winter, the microturbine runs at higher number of hours, which coincides with higher heat load directly supplied by the microturbine. This explains the higher dump energy during the winter months.

In cases 2–5, different values for both tilt and surface azimuth angles are taken into account to evaluate their effect on COE.

*Case 2*: Similar to case 1, but the tilt angle being considered is the one being optimized on the basis of maximizing the annual generated energy of the PV system, and the surface azimuth angle is the one that optimizes the minimizing COE.

*Case 3*: Similar to case 1, but the tilt angle being considered is the one being optimized, which also considers the minimization of the COE and the surface azimuth angle being the one optimized on the maximization of the PV annual energy production.

*Case 4*: Similar to case 1, but the tilt angle being considered is the one being optimized, taking into account the minimization of the COE and the surface azimuth angle being directed to the south.

*Case 5*: Similar to case 1, but the tilt angle being considered is the one being optimized on the basis of maximizing the annual

**Table 6**
Results of simulation of different cases.

| Case | PV type | Battery type | Microturbine type | PV fixture type | No of PV panels | No of battery units | No of microturbines | Tilt angle (°) | Surface azimuth angle (°) | COE ($/kW h) | Running hours of microturbine (h) | LLP (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Cases 1–20 are with microturbine as a backup source or without* | | | | | | | | | | | | |
| 1 | 4 | 4 | 1 | 1 | 92 | 20 | 1 | 30 | 14 | 0.2587 | 2692 | 0 |
| 2 | 4 | 4 | 1 | 1 | 92 | 20 | 1 | 32.8 | 14 | 0.2589 | 2696 | 0 |
| 3 | 4 | 4 | 1 | 1 | 92 | 20 | 1 | 30 | 16 | 0.2588 | 2694 | 0 |
| 4 | 4 | 4 | 1 | 1 | 92 | 20 | 1 | 30 | 0 | 0.2595 | 2711 | 0 |
| 5 | 4 | 4 | 1 | 1 | 92 | 20 | 1 | 32.8 | 0 | 0.2596 | 2713 | 0 |
| 6 | 4 | 4 | 1 | 2 | 80 | 19 | 1 | 36 | – | 0.2662 | 2778 | 0 |
| 7 | 2 | 2 | 1 | 1 | 117 | 8 | 1 | 29 | 14 | 0.2627 | 2764 | 0 |
| 8 | 4 | 2 | 1 | 1 | 87 | 8 | 1 | 29 | 17 | 0.2601 | 2760 | 0 |
| 9 | 2 | 4 | 1 | 1 | 120 | 20 | 1 | 25 | 15 | 0.2611 | 2726 | 0 |
| 10 | 1 | 1 | 1 | 1 | 149 | 6 | 1 | 30 | 14 | 0.2787 | 2780 | 0 |
| 11 | 3 | 3 | 1 | 1 | 92 | 11 | 1 | 30 | 12 | 0.2659 | 2777 | 0 |
| 12 | 1 | 3 | 1 | 1 | 150 | 12 | 1 | 29 | 12 | 0.2783 | 2774 | 0 |
| 13 | 1 | 4 | 1 | 1 | 137 | 23 | 1 | 30 | 14 | 0.2751 | 2865 | 0 |
| 14 | 4 | 4 | 1 | 1 | 88 | 19 | 1 | 29 | 14 | 0.2657 | 2921 | 0 |
| 15 | 4 | 4 | 1 | 1 | 80 | 12 | 1 | 29 | 16 | 0.3037 | 6366 | 0 |
| 16 | – | – | 1 | – | 0 | 0 | 2 | – | – | 0.3273 | 8760 | 0 |
| 17 | – | – | 1 | – | 0 | 0 | 2 | – | – | 0.3517 | 8760 | 0 |
| 18 | 4 | 4 | – | 1 | 490 | 337 | 0 | 40 | 13 | 0.5140 | – | 1.99 |
| 19 | 4 | 4 | – | 1 | 507 | 416 | 0 | 30 | 14 | 0.5752 | – | 0 |
| 20 | 4 | 4 | – | 1 | 459 | 302 | 0 | 30 | 15 | 0.4739 | – | 4.95 |
| *Case 21 is with diesel generator as a backup source* | | | | | | | | | | | | |
| 21 | 4 | 4 | 1 | 1 | 230 | 129 | 1 | 32 | 15 | 0.3982 | 624 | 0 |

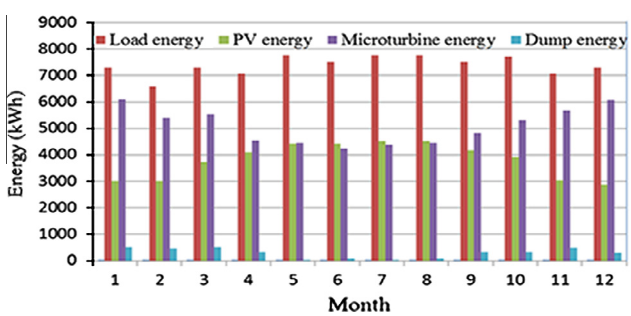


**Fig. 4.** Monthly PV panels generated energy, microturbine generated energy and dump energy.

generated energy of the PV system, and the surface azimuth angle is the one directed to the south.

It is noticeable that the difference between the values of COE for cases 1–5 is very small. So, the tilt angle optimized on the basis of maximizing the annual generated energy of the PV system and the surface azimuth angle directed towards the south can effectively be used without the need for additional mathematical manipulations while calculating these angles and accounting for other basis for evaluation.

*4.3.2. Evaluation of other cases rather than the main optimized case.*

*4.3.2.1. Effect of using single axis tracking system on COE instead of fixed mounting fixture. Case 6*: Similar to case 1, but considers PV mounting fixture type2. For this case, the number of PV panels required is less, as for these types of fixtures, the amount of PV annual energy production is greater compared to type1. This type follows the movement of the sun such that the surface azimuth angle is equal to the sun's azimuth angle, which increases the rate of energy being harvested.

*4.3.2.2. COE of selected cases considering different types of PV panels and battery units.* Cases 7–13 are the selected cases, where the types of components are specified, and the optimization is conducted based on the number of components.

*4.3.2.3. COE without utilizing the cogeneration feature of the microturbine. Case 14*: Similar to case 1, but the electrical output of the microturbine supplies both electrical and heat loads. It can be observed that utilizing the cogeneration feature of the microturbine will decrease the COE.

*4.3.2.4. Effect of the microturbine running on follow load mode on the COE. Case 15*: Similar to case 1, but the microturbine operates in such a way that its electrical output follows the changes of the electrical part of the load. In this case, the number of annual operation hours is more than twice the annual operation hours of case 1, while the total natural gas consumption is less than the quantity consumed for case 1. For case 1, the amount of annual natural gas consumption is 32,029 $m^3$, while the amount was 30,244 $m^3$ for this case. This is due to the fact that the microturbine natural gas consumption depends on the load connected to it, according to (4). Additional number of PV panels is required for this case as charging of the battery is the responsibility of these panels.

*4.3.2.5. Using microturbine as a standalone source.* In the following two cases (case 16 and case 17), the microturbine alone is used to supply the load with and without utilizing the cogeneration feature of the microturbine.

*Case 16*: Is the microturbine only scenario. For this case, the number of microturbines assumed to supply the load is two, and the electrical part of the load is only one being supplied (i.e. utilization of cogeneration feature). In this case, each microturbine operates half of the time. The annual fuel consumption of the first microturbine was 18,102 $m^3$, while the consumption of the second one was 27,252 $m^3$.

*Case 17*: Similar to case 16, but the two microturbines here supply the load (both the electrical and the heat loads). In this case, the annual natural gas consumption of the first microturbine was 21,843 $m^3$, while the second consumed 32,382 $m^3$.

In all of the previous cases, it is assumed that the load is completely covered throughout the year (no load interruption). This can be easily achieved without an obvious increase in the COE, especially for the cases of the PV/microturbine hybrid system (case 1–case 13). Switching the microturbine on-and-off can easily be done for these cases through signals from the battery.

*4.3.2.6. Standalone PV hybrid system.* In cases 18–20, the load demand is covered using only the PV and battery (i.e. without microturbine). The effect of considering different values for LLP on the COE is evaluated in these cases.

*Case 18*: A standalone (PV and battery without microturbine) system is assumed to be the case. A certain value for LLP (2%) is also assumed. The value of COE for this case is high when compared with the COE calculated for the optimized hybrid mentioned in case 1. It should also be noted that in this case, there are no pollutant emissions being released.

*Case 19*: Similar to case 18, but the reliability is 100% (i.e. zero load rejection). To satisfy this condition, additional numbers of PV panels and battery units are required, which increases the value of the COE. The increase in COE compared to case 18 is about 12%. This case may arise when critical loads are required (no interruption of power supply is allowed), and is being located far from the grid. Medical clinics and remote telecommunication stations located in remote areas without the availability of natural gas as a fuel are examples of this case.

*Case 20*: Similar to the previous two cases, but with a value for LLP equaling 5%. The COE is lower compared with the previous two cases. The decrease in COE compared to case 19 (zero load rejection case) is about 17.6%.

*4.3.2.7. Evaluation of using diesel generator as backup source instead of microturbine. Case 21*: In this case, a diesel generator is regarded as a standby source instead of the microturbine. As the price of diesel is high in the Palestinian Territories (1.77 $/l), the number of the PV panels and the battery unit increases compared to case 1, where the microturbine is selected to operate as a standby source. For this case, the number of diesel generator annual running hours is less than 25% of the total microturbine running hours. The increase in COE for this case compared with case 1 is about 54%. Although the number of microturbine running hours is 4 times more than the running hours of the diesel generator when it is used as a standby source, the annual cost of the gaseous emissions is lower. For the microturbine case, it is about 735.5 $/year, whereas for the diesel generator case, it is about 951 $/year.

*4.3.3. Design of the hybrid system-best optimized case*

As provided for in Table 5, the number of PV panels for the best optimized case (case 1) is 92 panels, while the number of battery units is 20 units. The DC bus voltage recommended for this system rating is 48 V. The rated voltage of the battery-optimized type is 2 V, so 24 battery units are required to be connected in series to provide the recommended DC bus voltage. This means that an additional 4 units are needed that raises the COE to 0.2624 $/kW h. The optimized PV panel type has a maximum power point voltage equaling 29.8 V. This means that 10 PV panels of this type should be connected in series to form a string. As the optimized number of the PV panels is 92 panels, 9 strings should be connected in parallel. In this case, 90 panels are required for this installation. The COE accounted for 24 battery units (instead of 20) and 90 panels (instead of 92) as 0.2617 $/kW h.

The output rated voltage of the charger regulator should be 48 V, while its input voltage rating should withstand the PV array open circuit voltage ($10 * 36.9$ V = 369 V). The charger regulator power rating should not be less than the peak power of the PV system, and is chosen to be 25 kW. For these charge regulator ratings, a built in maximum power point circuit is recommended to be included in their design [3].

The bidirectional inverter is selected such that its input voltage rating is 48 V (DC), while the ratings of its output are: 3 phase, 50 Hz, 400 V (AC). The maximum peak power in the load curve is 19 kW, so the bidirectional inverter power rating is selected to be 25 kW. The ratings of the microturbine are: three phase, 10–60 Hz, 30 kW, and 360–480 V AC.

*4.3.4. Generalization of results*

The feasibility of using a microturbine as a standby source in hybrid energy systems can be generalized. This conclusion came from the fact that the feasibility of using a diesel generator as a standby source in hybrid energy systems, especially for remote applications that has been proven by many previous research works and the feasibility of using microturbines as standby sources instead of using diesel generators for this purpose has been proven in this study.

As indicated before, the optimized scenario is the PV/microturbine hybrid system. Actually, this study that analyzed in detail this hybrid system in which the microturbine is utilized as a backup source is one of the first published studies in this field. To the best knowledge of the authors, there are no installed systems of this type around the world that its results have been published and can be utilized as an experimental bench for comparison purposes with the simulation results of this study. The same applies for the Palestinian case when the PV/microturbine optimized scenario has been considered. The authors actually hope that the results of this study may encourage one of the institutions in Palestine (government or non-government) to install this optimized PV/microturbine scenario so as to be a pilot project that may be utilized for further analysis.

However, and considering the Palestinian case, number of PV/diesel generator hybrid systems has been implemented to supply number of remote communities in Palestine. Most of them have been implemented under the supervision of Energy Research Center at An-Najah National University, while others have been implemented under the supervision of NGOs. The rating of the PV system is in the range of 5–30 kWp for each. The implementation of these projects proves that it is feasible and possible to conduct such projects despite the different challenges it faces. One of these projects is Atouf village (northern part of the West bank) electrification. This project was established on December 2007. The rating of the PV panels in this project is 11.7 kWp, the battery bank is 120 kW h and the diesel generator rating is 20 kV A. The performance of the system was monitored for 6 months. The economic analysis after this period of monitoring indicated that the COE production was about 0.65 $/kW h. The same analysis appeared that the COE by the diesel only scenario was around 0.75 $/kW h [32]. The COE production for the hybrid PV/diesel scenario considered in this study as indicated in Table 6 is 0.398 $/kW h. The decrease in COE production compared to the Atouf project is due to decrease in capital costs of the various components in the near past years. As indicated in the same table, the COE for the PV/microturbine hybrid system is less when compared with other scenarios.

## 5. Conclusions

The purpose of this study was to model an optimal design of a PV/battery/microturbine hybrid energy system to supply power to remote communities in Palestine. The cost of global warming emissions was taken into account in this optimization analysis.

The results of the analyses in this paper indicate that the scenario where the hybrid system is made up of a combination of the PV panels, battery units, and a microturbine as a standby source represents the most economical option.

The case where the microturbine runs at its rated power (not follow load mode) to provide the electrical portion of the load, while the cogeneration feature of the microturbine was utilized to directly supply the heat load was found to be the most economical case. The COE for this case is 0.259 $/kW h. For a load curve that has an average of daily energy equaling 243 kW h with a maximum peak power in this load curve equals 19 kW, it was found that 92 panels (21.62 kWp) and 20 battery units (25.92 kW h) are capable of supplying this load with zero LLP. The microturbine (30 kW rated power) is required to run as a backup source for 2692 h annually. The contributions of the PV panels and the microturbine vary from one month to the next.

The feasibility of using microturbines as standby sources instead of using diesel generators for this purpose has been proven in this study. The diesel generators can be effectively subsisted in hybrid renewable energy systems, but the fact that small ratings of microturbines (<25 kW) are not present in the market nowadays limits the distribution of microturbines.

The COE for residential applications in Palestine is about 0.19 $/kW h. The COE from our suggested hybrid system is higher than electrical purchases from utility companies. If remote sites that are located far from the existing grid and/or the gaseous emissions were taken into account, the implementation of such hybrid systems will seem more acceptable. Moreover, the decrease in prices of microturbines and the PV system components will encourage more acceptance and deployment of these energy systems in a not-to-distant future.

## Acknowledgements

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