Chapter

Hybrid Wind and Solar Systems Optimization

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Abstract

Solar and wind energy systems are considered as promising power-generating sources due to their availability and advantages in local power generation. However, a drawback is their unpredictable nature. This problem can be partially overcome by integrating these two resources or more in a proper combination to form a hybrid energy system. Nevertheless, the harmonization of different energy sources, energy storage, and load requirements is a challenging task. Thus, the performance of various possible configurations has to be investigated to reach the optimum combination using a simulation program. The number of simulations and time required for calculation increases with the increase in number of optimization variables. Therefore, the selection of a quick and accurate optimization technique is very important. Different software packages, such as HOMER and iHOGA, were developed, where each of them is based on a different optimization algorithm.

Keywords: hybrid energy system, optimization, hybrid energy packaged, energy management

1. Introduction

It is currently observed that the rapid development of new electrical power sources is denominated by renewable sources for both cases: on-grid and off-grid. The main problem of off-grid stand-alone renewable energy systems (RES) is the fluctuation of power supply which can be avoided using hybrid solar/wind energy systems (HSWES) that allow improving the system efficiency, increasing power reliability, and reducing energy storage requirements for stand-alone applications [1].

In order to solve sustainability and power quality problems, the power transfer from the renewable sources to load must be managed in a proper way. Therefore an energy management process should be proposed to prevent power discontinuity or power wasting so that the loads operate properly.

A major aim of HSWES optimization is to reach the suitable size of each component and the control strategy that provide reliable, efficient, and cost-effective system. Optimization is performed by minimizing (or maximizing) an objective function using a suitable criterion such as net present cost (NPC) and/or the generated electricity price (EP). In this case the cost of avoided CO_2 emissions should be taken into consideration [2].

2. Hybrid renewable energy systems

Renewable energies are intermittent sources; hence, hybrid renewable energy system (HRES) is considered an appropriate solution to support electrical requirements especially for remote areas. HRES that incorporates more than one type of renewable energy technologies in a site can help to mitigate the effect of intermittent nature that some of them exhibit and to reach a sustainable source.

As mentioned before, wind and solar systems are considered favorable sources for energy generation due to their availability and being site-power generation. However, a drawback, common to solar and wind utilization, is their unpredictable nature and dependence on weather changes; both of these energy systems would have to be oversized to make them completely reliable. Fortunately, the problems caused by variable nature of these resources can be partially overcome by integrating these two resources or more in a proper combination to form a polygene ration energy system.

HRES is an energy system that includes a number of units and equipment. Different technologies usually exist for alternative types of each of these units. Selecting the optimal alternatives is challenging; to achieve a greater knowledge of how a HRES is designed and optimized, an optimization tool should be used.

3. Optimization techniques

The optimization process is followed through an objective function (OF) with respect to some variables in the presence of constraints on those variables. The objective function is either a cost function or energy function which is to be minimized, or a reward function or utility function, which is going to be maximized [3, 4].

An optimization technique is used to find an optimized solution for a particular optimization model. "Optimum" is the word that is used to demonstrate the meaning of best, either maximum or minimum [4]. Problems dealing with the cost will require the best cost to be as less as possible. On the other hand, problems dealing with profit will see the maximum value as the best answer. There are several well-known optimization techniques depending on the model type, deterministic or stochastic, such as:

1. Linear programming (LP), a type of convex programming, is applied in the cases in which the OF is linear and the constraints are specified using only linear equalities and inequalities.

2. Second-order cone programming (SOCP) is a convex program and includes certain types of quadratic programs.

3. Integer programming is applied in the case that some, or all, variables of the linear solution are constrained to have an integer value. This is generally more difficult than linear programming.

4. Quadratic programming permits the OF to have quadratic terms, while the feasible set of solution must be identified with linear equalities and inequalities. Some specific cases of the quadratic term lead to a type of "convex programming."

5. Fractional programming is concerned with the optimization of ratios of two nonlinear functions. The special class of "concave fractional programs" can be transformed to a "convex optimization" problem.

6. Nonlinear programming is used for the general case of the objective function and/or the constraints containing nonlinear parts. Cases of convex program affect the difficulty of the solution.

7. Stochastic programming is applied when some of the constraints or parameters depend on random variables.

8. Combinatorial optimization is applicable when the set of "feasible solutions" is, or can be, reduced to a discrete one.

9. Infinite-dimensional optimization is applied in the case that the set of "feasible solutions" is a subset of an "infinite-dimensional space."

10. Stochastic optimization is used in the case of random function measurements or random inputs.

11. Robust programming is, like stochastic programming, an attempt to capture uncertainty in the data underlying the optimization problem. Robust optimization targets to find solutions that are valid under all possible realizations of the uncertainties.

12. Heuristics and "metaheuristics" use limited or no assumptions concerning the problem being optimized. Usually, heuristics do not guarantee that an optimal solution has to be found. In fact, heuristics are used to find approximate solutions for complicated optimization problems.

In addition to these techniques a growing interest in the application of artificial intelligence (AI) techniques to power system engineering. AI techniques, unlike strict mathematical methods, have the ability to adapt to nonlinearities and discontinuities commonly found in power systems. The best known algorithms in this class include:

- Evolution programming
- Genetic algorithms
- Simulated annealing
- Tabu search
- Neural networks

4. Optimization of HRES

As power system must be sustainable, secure, and environmentally safe, the basic function of a HRES is to supply power with quality electrical energy, reliably and economically. As such, optimization plays an important role. This enables to minimize the cost of operation, initial investment, and environmental impacts and maximize reliability, quality, and efficiency.

The optimization of **HRES** used to analyze the system is mainly focused on two problems: (1) determine the optimal configuration of the power system and optimal type and sizing of generation units installed, and (2) design strategies for optimal dispatch, which are subject to constraints of the system meeting load requirements at minimum cost.

4.1 Costs

To reach an appropriate HRES the system should be designed according to techno-economic and environmental measures to fulfill physical and operational constraints. For cost optimization, system design seeks the configurations and control strategies that achieve the lowest total cost over the system lifetime. The lifetime cost which subjects to the system typically consists of two or more components. The life of the system is usually considered to be the life of the PV panels—which are the elements that have a longer life-span.

The OF in this case is the system net present cost (NPC), which consists of initial investment cost in addition to the discounted present worth of all future costs over the system lifetime. The system cost is the sum of all its components, e.g., PV, WT, battery, converter, and any other necessary devices, in addition to installation cost. Component costs comprise all costs: capital, replacement, operational and maintenance, and fuel consumption. Some of these costs depend on the selected control strategy.

4.2 HRES optimization model

For PV/WT/DG/battery bank system, the objective is to minimize the net present cost (NPC) under load and power constraints [5]:

$$\text{Minimize } NPC = \sum C_{PV_i} + \sum C_{W_j} + \sum C_{DG_l} + \sum C_{B_m} + \sum C_{C_n} \tag{1}$$

Subject to the constraints

$$\sum Load \le \sum E_{PV_i} N_{PV_i} + \sum E_{W_j} + \sum E_{DG_l} \tag{2}$$

$$(\text{Power Wattage})_{\max} \le \sum P_C N_C \tag{3}$$

$$\boldsymbol{SOC}_{\min} \le \boldsymbol{SOC}\ (\boldsymbol{t}) \le \boldsymbol{SOC}_{\max} \tag{4}$$

where *CPVi*, cost of a photovoltaic module; *CWj*, cost of wind turbine; *CDGl*, cost of a diesel generator; *CBm*, cost of a battery; *CCn*, cost of a converter; *NPVi*, number of photovoltaic modules; *NWj*, number of wind turbines; *NDGl*, number of diesel generators; *NBm*, number of battery bank to be used; *NCn*, number of converters; *PC*, power of converter; *EPVi*, kWh generated by the *ith* photovoltaic module; *EWj*, kWh generated by the *jth* wind turbine; *EDGl*, kWh generated by the *lth* diesel generators; and ***SOC***, state of charge of the battery.

The common current optimal sizing tool is the available software packages that can be helpful for real-time system integration.

5. Optimization software packages

The number of simulations and time required for calculation increases with the increase in number of optimization variables. Therefore, the selection of a quick and accurate optimization technique is very important.

Simulation software tools are the most common tools for evaluating performance of the hybrid solar/wind systems. Connolly [6] listed 67 software tools available for analysis of hybrid energy systems, studied 37 of them, and identified the suitable tools for different objectives. Some of the most widely used software tools for hybrid energy systems are summarized as follows:

5.1 iHOGA

Improved Hybrid Optimization using Genetic Algorithm (iHOGA) is a simulation and optimization software developed in C++ by the Electric Engineering Department of the University of Zaragoza, Spain [7]. This software is a tool for optimum sizing of hybrid renewable energy system. This tool uses double genetic algorithms for optimization. The main algorithm is used for the system components while a secondary algorithm is added for control strategy. The software can simulate and optimize system of any size (size from Wh to MWh even through GWh daily consumption). Optimization is achieved by minimizing total system costs through its useful lifetime. The program allows mono-objective as well as multi-objective optimization. The mono-objective and multi-objective optimizations are achieved for stand-alone and grid-connected hybrid renewable energy systems. The program modeling provides various outputs such as size of the PV generator in Wp and its ideal tilt, battery capacity in kWh, battery lifetime in years, initial investment, NPC with breakdown of the component, lowest cost of energy, and CO_2 emissions of the system in CO_2/kWh [7].

Dufo-López et al. used iHOGA software for the optimization of the electrical supply of a hospital existed far from the electric grid in Kalong (Democratic Republic of the Congo), which is presently powered by a diesel-battery system [8]. The results showed that adding solar photovoltaic (PV) to a diesel-battery system to supply the required load could obtain a 28% reduction in energy cost and 54% reduction in the fuel consumption reducing CO_2 emissions lower than the current diesel-battery system.

Fadaeenejad et al. presented an analysis and optimization for a HRES (PV/WT/BAT), which are designed for rural electrification in Malaysia [9]. The evaluation of the performed optimization was accomplished using iHOGA software. The obtained results illustrate that the wind energy is used as a supportive source of energy for many locations in Malaysia, and the hybrid renewable energy systems are cost-effective for these rural areas.

Anita Gudelj et al. presented an optimal sizing model for hybrid energy system (HES) that aims to minimize the total cost through the useful life of the system and CO_2 emissions to meet the desired consumption [10]. The iHOGA program was used to simulate the system operation and calculate technical economic parameters for each configuration. The results showed that the hybrid energy systems have considerable reductions in CO_2 emission and cost of the system. Using a diesel generator as a backup source, for the PV/WT/battery system, was found to be the best solution to guarantee the reliable supply without any shortage of the required load under the weather data change.

5.2 HOMER

The National Renewable Energy Laboratory (NREL) introduced a Hybrid Optimization Model for Electric Renewable (HOMER) package. HOMER uses hourly load and weather data inputs to perform hourly simulations for techno-economic analysis of hybrid energy systems [11]. HOMER performs three tasks: simulation, optimization, and sensitivity analysis. It facilitates the optimization of simulated renewable energy systems to minimize NPC for a given set of constraints.

Mustafizur Rahman et al. [12] suggested seven scenarios of combining hybrid renewable energy technologies with diesel generator to minimize the economic and environmental concern effects of its use. The suggested scenarios were (100, 80, 60, 50, 35, 21, and 0%) renewable resource penetration. A case study for the remote community of Sandy Lake, Ontario, was conducted. The different scenarios modeled are developed by using HOMER software. The aim of this study was to find the best combination of hybrid renewable energy systems from the available resources for a particular off-grid location in Canada. The results showed that using 80% renewable energy scenario can achieve the demand with 72% higher COE but 83% lower CO emissions than 0% renewable fraction—100% diesel-battery scenario.

In a similar study, Ngan et al. [13] focused on the technical and economic feasibility of "the hybrid energy systems (PV/WT/DG)" in a southern city of Malaysia using HOMER simulation software. They considered seven different system configurations: stand-alone diesel generator system, hybrid PV-diesel system, PV-diesel system with battery storage, hybrid wind-diesel system, wind turbine-diesel system with battery storage, wind-solar-diesel system, and wind-solar-diesel system with battery storage.

Targeting to study technical and economic performance of wind/diesel/battery (W/D/B) system supplying a remote small gathering of six families, HOMER package was used [14]. Net present cost (NPC) and cost of energy (COE) are used as economic criteria, while % of power shortage is the measure of performance. Optimum system configurations are estimated for two sites. Simulation results showed that W/D/B systems are economical for the assumed community sites as the price of generated electricity was about 0.308 $/kWh, without taking external benefits into considerations. W/D/B systems were found to be more economical than diesel-alone system.

A case study of the performance and optimization of a HRES supplying a water desalination system for irrigating a small greenhouse hydroponic cultivation was presented by Khatab et al. [15]. The study presented optimization of two hybrid systems: photovoltaic/wind turbine (PV/WT) with and without backup diesel generator. The results showed that COE of PV/WT system is less than that of PV/WT/diesel, while there is no capacity shortage in the case of PV/WT/diesel.

5.3 RETScreen

It is developed by Natural Resources Canada to evaluate the energy production, costs, emission reduction, and financial viability for various types of renewable and nonrenewable energy systems [16]. It performs economical comparison between conventional system and proposed system. A study examined the potential for a 10-MW PV power plant in Abu Dhabi using RETScreen modeling software to forecast the produced energy, financial feasibility, and GHG emissions reductions [17]. Initial results showed high energy production potential and saving a high amount of tons of GHG emissions annually.

5.4 HYBRID2

This software package is developed by the National Renewable Energy Laboratory (NREL) of the United States Department of Energy in cooperation with the University of Massachusetts. This hybrid simulation software can run simulation for time intervals from 10 mintues to 1 hour. The NREL recommends the HYBRID2 for the thermal loads [18].

5.5 TRNSYS

TRNSYS is a transient system simulation program developed by the Solar Energy Laboratory, University of Wisconsin-Madison, USA. It has a modular structure in which components of the system are specified by the user [19]. It can simulate almost all thermal and renewable power generation systems.

5.6 Other applications of different packages

A review of the optimization techniques used to select HES that minimize initial and operating cost was presented by Erdinc and Uzunoglu [20]. The compared techniques were (GA), "simulated annealing" (SA),"particle swarm optimization" (PSO), and HOMER. The approach for component sizing is based on demanded load, renewable resources availability, and climatic conditions.

For a touristic resort in Malaysia, Hossaina et al. [21] suggested a stand-alone HRES that includes WT, PV, DG, converter, and battery as energy sources to replace the existing diesel generators. The estimated daily average and peak load were 13,048 and 1185 kW, respectively. The system techno-economic was achieved using HOMER software, and the results exhibited that the hybrid system has lower NPC and COE than the existing diesel system.

In a similar study, Olatomiwa et al. [22] investigated different (PV, WT, and DG) power configurations in six "geopolitical" zones of Nigeria, also by HOMER [23]. The result denoted that the PV/DG/battery system configuration is the optimum configuration in the cases of diesel fuel price of $1.1–1.3/l, exhibited lower fuel consumption, and reduced CO_2 emission.

"HOMER" was also applied to investigate the possibility of providing 200 households in remote area in Ethiopia with electricity using HSES [24]. The results revealed that PV/DG/battery system is the most "cost-effective" using load following strategy. The authors concluded that this study could be considered applicable for similar climatic condition regions.

Another comparable feasibility analysis of (HRES) supplying load requirements of a rural village, of 50 families, in Bangladesh, far from the grid was performed using "HOMER package" [25]. The "annual average load" was 213 kWh/day; the results indicated that for this location, load profile of the feasible system is also PV/WT/battery where the NPC had a total of $224,345 and COE of 0.161 $/kWh with no CO_2 emission.

A fuzzy logic power controller was proposed by Alam et al. [26] to provide continuous power supply, from a hybrid WT/PV/fuel cell power system with battery, for remote area. The simulated system configuration was 20 kW WT, 80 kW PV array, and 10 kW fuel cell. Excess power was directed to the batteries first and then to the electrolyzer. In the case the optimum system, the results showed that power shortage had reached 254 kWh/year, which represented a high percentage of the total load. Also the estimated cost of energy was very high (1.045 $/kWh).

Ajao et al. [27] performed an economic analysis of PV/WT system for a Nigerian area. The authors concluded that the proposed system is expensive because of high capital and installation costs. The authors did not take into consideration the reduction of greenhouse gas emission which would improve the cost-effectiveness of the system.

Seeking the optimum design of economically feasible HES to feed a load which had seasonal variations, Fulzele et al. used iHOGA to simulate and optimize the system [28]. The results showed that 99% of the required load was covered by the system, subject to operational constraints and control strategies. Nevertheless, the results did not take into consideration that the excess energy was about 25% and minimizing this value would reduce the cost of energy (COE).

6. Energy management

Energy management is considered as an optimization action. Energy management increases usable energy, decreases wasted energy, and has the additional benefits of optimizing energy systems and improving their reliabilities.

The electrical power generated by renewable sources such as wind and solar power is affected by environmental conditions resulting in problems in load side. When there is no sun or the weather is cloudy, the power amount to be generated by solar energy changes. Accordingly, wind does not blow at the same speed all the time; it is discontinuous. Henceforth, energy amount to be generated from these sources is variable. Energy management processes are developed to prevent problems like discontinuities that occur due to either weather changes or sudden load changes.

Different methodologies and techniques used to develop a successful energy management strategy, for both stand-alone hybrid renewable energy systems and the grid-connected hybrid renewable systems, were investigated by Olatomiwa et al. [22]. The authors focused on energy management based on "linear programming," "intelligent techniques," as well as energy management by "fuzzy logic controller." The authors emphasized that selecting the suitable energy management strategy is necessary to control the energy flow in the system that increases reliability, decreases electricity shortage, reduces the "COE," and increases the system lifetime.

In a study that investigated the performance of various possible configurations using iHOGA software, the achieved optimum configuration was further improved by adapting the daily load pattern to the periods of high renewable generated energy to increase direct energy utilization rather than charging batteries [29]. This will result in effective minimization of battery bank size.

7. Case study in an Egyptian farm

The study objective was to design and simulate HSES for remote area in Egypt. The study was performed using iHOGA simulation and optimization package to decide on the optimal size of each component and control strategy. The input data for the optimization are weather data of the selected location, nominated system component cost, and technical parameters. Financial parameters, interest and inflation rates, installation, and operational costs are also included. The proposed system components are PV/WT/batteries/DG/inverter and charge regulator. The suggested load in this case study is energy required for a desalination unit (DU). The system is installed in NRC farm in Noubarya. The considered system configuration is shown in **Figure 1**.

NRC farm is in a remote area that is located between 30°40′0" N and 30°4′0″ E. The average temperatures for winter and summer are about 14 and 28°C, respectively. The farm is a research pilot plant for agriculture, animal, and fish production. Frequent electricity shortage is observed due to instability of low-voltage grid power in the area.

7.1 Load profile (base case)

In this case study, the HSES provides a reverse osmosis desalination unit (DU) with electricity. The required daily desalinated water is about 60–65 m^3. The required power for the DU is the sum of powers required for three types of pumps included in the DU: "5 HP high-pressure pump" (3728 W), "distribution pump" (1000 W), and a "feed pump" (1870 W in the case of feeding rate is 7 m^3/hour).

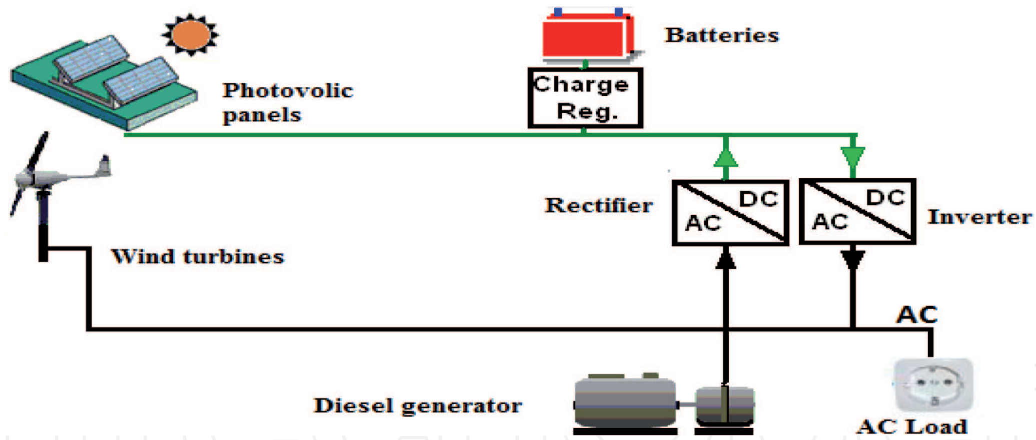

Figure 1.
The system configuration.

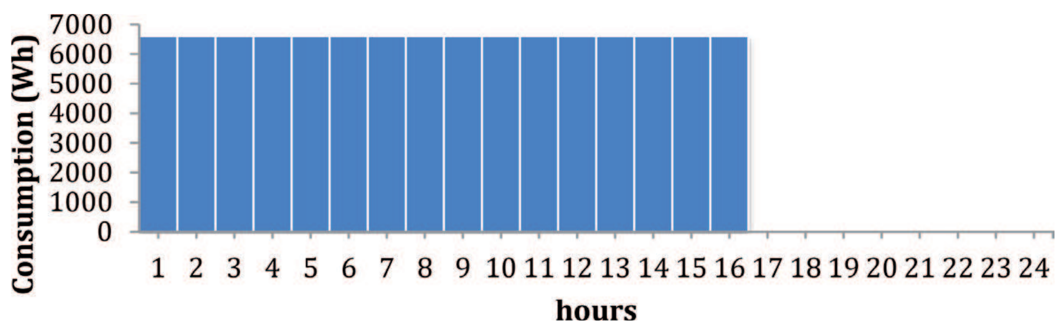

Figure 2.
DU base case load profile (base case).

To produce 60–65 m^3/day, the DU should be fed by 110 m^3 of brackish water per day. The first suggested load profile in this study; referred to as base case, the high-pressure pump, the distribution pump, and feed pump are designated to work simultaneously. Hence, the peak load requirement is about 6.6 kW continuously from 00:00 to 16:00, and the average estimated daily energy consumption is 105.6 kWh (**Figure 2**).

7.2 Resource input data

The input climatic data for the proposed site are obtained from NASA Surface Meteorology and Solar Energy [30]. **Table 1** represents the monthly average of solar radiation and wind speed data for the selected area.

7.3 System description

As mentioned above, the system components are PV, WT, inverter, batteries, and DG. A number of monocrystalline and polycrystalline PV modules (in the range of 100–280 W/panel) were used in the simulation to select the suitable size. The initial panel cost is in the range of $143–455, while O&M cost of each panel is 1.43–4.55$/year. The panels' lifetime is considered to be 25 years. The WT types used in simulation are "Bornay" and "Hummer," both of 3–30 kW power range, and its hub height is considered to be between 15 and 18 m. The initial cost of WT is between $9821 and 44,200, its replacement costs $7800–33,800, and O&M cost $196–884/year. The lifetime of "Bornay" and "Hummer" are assumed to be 15 and 20 years, respectively. A backup DG is 3–4 kVA, and the battery bank is in the range of 180–3360 Ah with 80% depth of discharge used. The system also comprises an

Month	Solar radiation (kWh/m^2)	Wind speed (m/s)
Jan	2.92	3.8
Feb	3.78	4.1
Mar	5.10	4.1
Apr	6.40	3.9
May	7.40	3.9
Jun	8.13	3.8
Jul	7.92	3.8
Aug	7.24	3.8
Sep	5.93	3.8
Oct	4.38	3.7
Nov	3.22	3.6
Dec	2.69	3.8
Average	5.43	3.8

Table 1.
Noubarya solar and wind data [30].

inverter which is scaled according to the maximum peak load. The inverter type is ACME: 8000VA CARG. The above-stated values are attained from iHOGA database.

7.4 Control strategies

The software package used in this study is *iHOGA*, which offers two control strategies: load following and cycle charging strategy. In the first the priority is to meet the load at any given time. Hence, if the generated power from the HES is not enough to cover the whole load, the battery covers the rest of the demand. If the battery bank cannot cover the whole rest of the demand, the DG will operate.

In "cycle charging strategy," if the total (PV&WT) generated energy is greater than the load requirements, the excess energy charges the batteries. When batteries' state of charge (SOC) reaches its maximum value, the charging process is set off, while if (PV&WT) energy is lower than the load, the rest is covered by the battery bank. If the battery charge drops to its minimum SOC, the controller unit sets off discharging process and turns DG on to cover the unmet load. As it is well known, it is better to run the DG at its rated power to reach higher efficiency of fuel consumption; DG will serve the load and the extra power and, if any, will be used to charge the batteries to its maximum SOC.

Both of the above strategies are examined to select the optimal strategy for the given system constraints.

7.5 Objective function

The main target of the suggested system design is to reach the optimum solution of a HRES in terms of economic and technical conditions subject to the operational strategies and physical constraints. In this method, the possible optimum system configuration is the one that satisfies the user-defined constraints in accordance with the objective function. The objective function is to minimize NPC which consists of initial cost, replacement cost, maintenance, and running cost of system components like PV, WT, DG, batteries, converter, and etc. [10, 12, 31].

Objective function:

$$NPC = Min \sum T_c + T_r + T_{O\&M} \tag{5}$$

where T_c is the total capital cost of different components and T_r is the total replacement cost and $T_{O\&M}$ is the total cost of operation and maintenance in dollars.

There are many constraints that are considered to ensure that the generated electricity would cover the load such as the minimum renewable fraction (75%), levelized cost of energy (5 $/kWh), and the maximum percentage of annual unmet load which is defined to be 5%.

8. Results and discussion of base case

The suggested system is simulated to reach the optimum value of the selected objective function under the following constraints: minimum renewable fraction (RF) 75%, levelized cost of energy 5 $/kWh, and the maximum percentage of annual unmet load 5%. The simulated optimization results (for base case load) are shown in **Figure 3**.

Figure 3 exhibits the estimated optimum NPC and CO_2 emission of a number of simulation runs. The optimization results of the base case showed a minimum NPC of $162,034, COE of 0.17 $/kWh, and unmet required load of 1.3%. HSES optimum configuration is 53 parallel series of PV panels, 4 modules each of 100Wp rated power, 24 batteries connected in series each of 1340 Ah, 1 WT of 14.7 kW at 14 m/s, 8 kVA inverter, and 3 kVA (AC) diesel generator. **Figure 4** illustrates the annual distribution of energy generation.

It is observed in **Figure 4** that almost all the yearly demand, except 495.8 kWh/year, is fulfilled by the HSES generated energy, which account for less than 1.5% of total load, the CO_2 emissions of 11,950 kg/year. It could be also observed that the energy charging batteries are 10,768 kWh/year, (about 21% from the total generated power), and the excess energy is 8278 kWh/year, (about 16%).

The total generated energy is about 50,800 kWh/year, while the total load that is directly supplied by energy sources is 28,386 kWh/year, so the utilization of the energy sources is about 55.9%. As the efficiency of both inverter and battery charger is high, 98 and 95%, respectively, then the main losses result from battery charging and discharging efficiency which is 85%. As the charging and discharging energy amounts to 20,407 kWh/year, then energy losses are about 3000 kWh. The cost of different HSES simulated components are shown in **Table 2**.

It could be seen from the above table that the major cost items are PV panels and "battery bank" which represent about 23 and 22.8% of the total NPC. The high cost

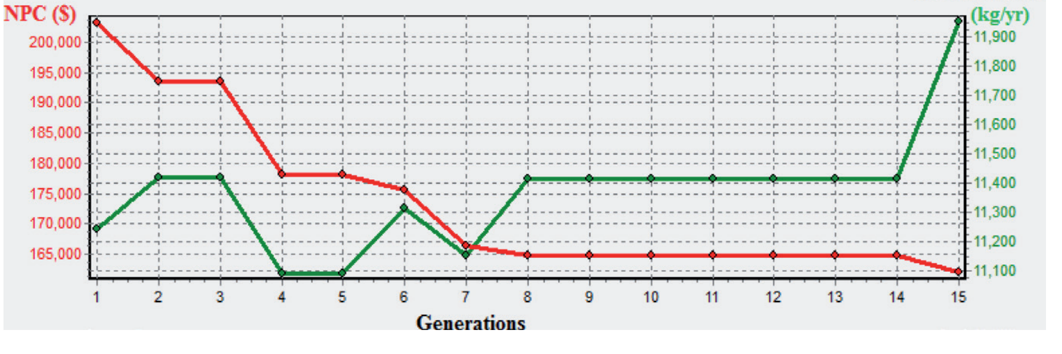

Figure 3.
Results of NPC as a function of generations.

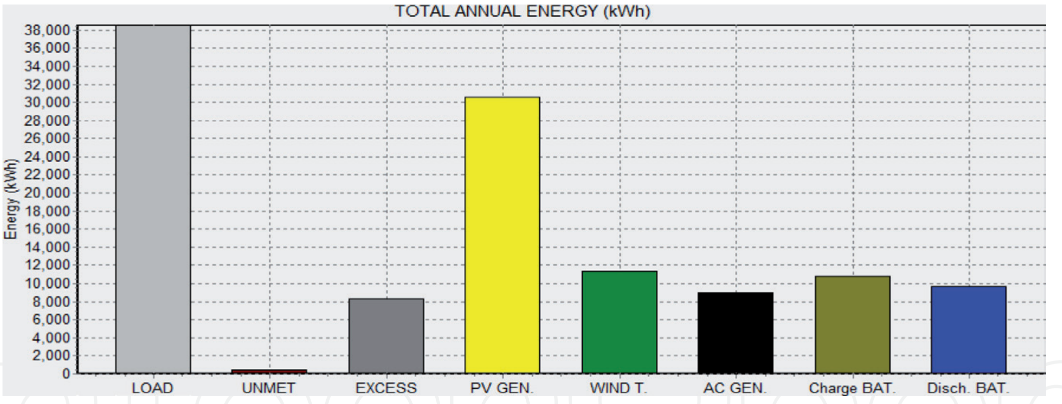

Figure 4.
Annual distribution of energy.

Cost element	Initial cost ($)	Percentage (%)
PV panel cost	37,282	23
WT cost	27,246	16.8
DG cost	21,667	13.3
Battery bank cost	36,940	22.8
Inverter cost	10,952	6.7
DG fuel cost	16,687	10.3
Charge reg. cost and AUX	11,256	6.4

Table 2.
Component costs of the optimized HSES.

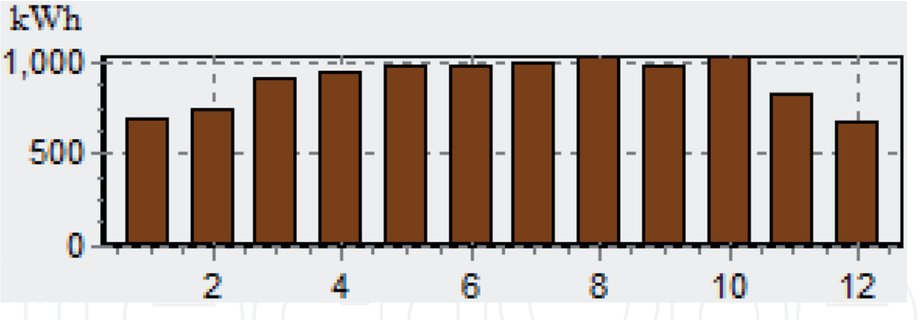

Figure 5.
Monthly average energy charging battery.

of the "battery bank" indicates that power generation profile does not match the load pattern; therefore a considerable part of generated energy has to be stored to cover the load when generated energy is not enough.

Regarding energy management, the main objective is to cover the DU load while minimizing the NPC and accordingly the cost of water desalination. From the results of the base case simulation, it is clear that, at some periods, a considerable amount of the generated energy does not match the load profile; therefore, it is directed to charge batteries. Hence, the amounts of energy charging the batteries and "excess energy" are excessive in some months as exhibited in **Figures 5** and **6**. Reducing these values would improve the system performance; hence, the configuration should be further adapted by means of load pattern managing. Load profile management could be achieved through matching its pattern with the power generation profiles. This would decrease the number and cost of batteries and consequently the total NPC.

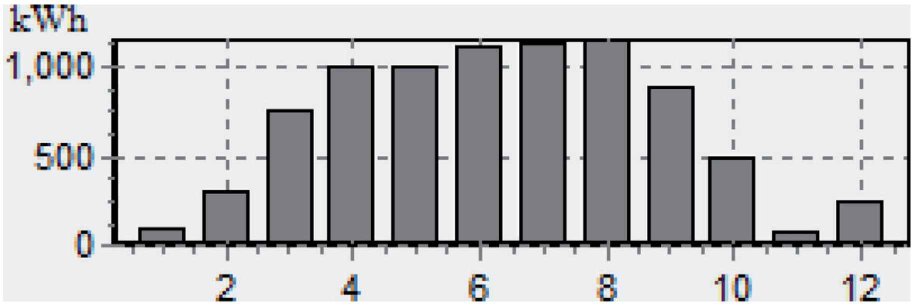

Figure 6.
Monthly average excess energy.

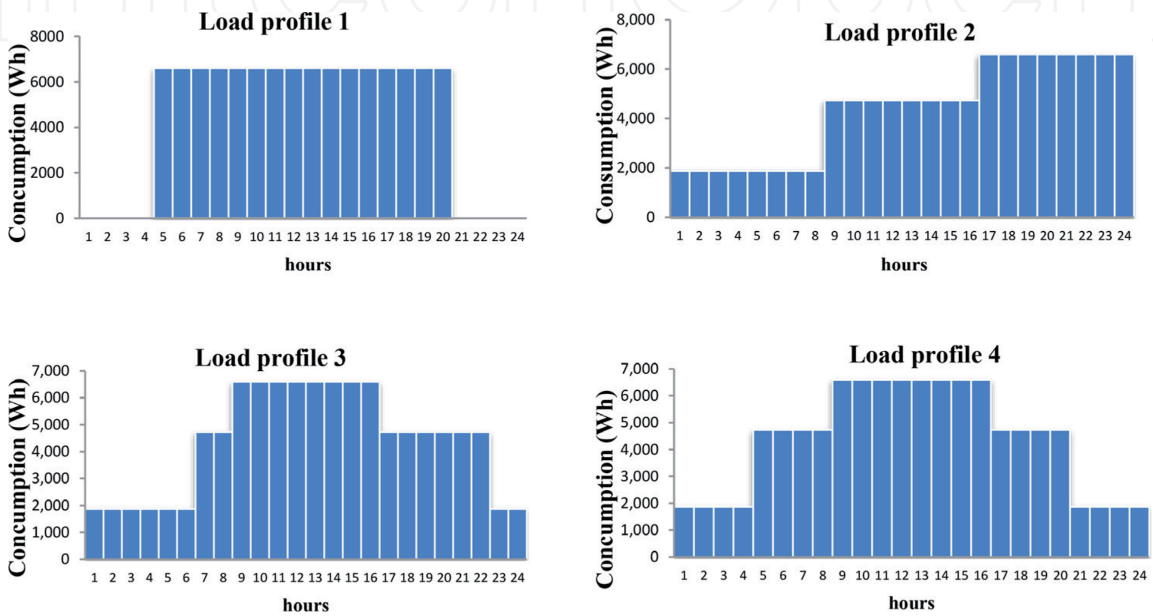

Figure 7.
Suggested load profiles.

Considering the hourly simulation results for the highest months of excess energy and energy charging battery amounts, different load patterns were proposed and simulated, of which the following four arrangements represented the most promising patterns to increase the direct utilization of the generated energy as shown in **Figure 7**.

As exhibited in **Figure 7**, the suggested load profile 1 proposed that all pumps are turned on from 05:00 to 21:00 requiring 6600 kWh. Load profile 2 schedule is based on the assumption that the "feed pump" is running from 00:00 to 08:00, while the "high-pressure" and "distribution" pumps are scheduled from 08:00 to 16:00. Finally all pumps work simultaneously from 16:00 to 24:00 as shown in **Figure 8**. This pattern is scheduled to fit high power period that is generated from the PV panel in the middle of the day and also the wind power at the night which is the period of high wind speed.

"Load profile 3" is arranged as feed pump running from 00:00 to 06:00 and from 22:00 to 24:00, while "high-pressure" and "distribution" pumps begin to work simultaneously, along with the "feed pump," from 08:00 to 16:00. The feed pump is switched off from 06:00 to 08:00 and 16:00 to 22:00, while the other two pumps remain operating. In the case of proposed "load profile 4," the feed pump schedule is running three periods: from 00:00 to 04:00, from 20:00 to 24:00, and from 04:00 to 08:00. The "high-pressure" and "distribution" pumps start working when the feed pump is switched off except from 08:00 to 16:00 when all the pumps are working simultaneously. This profile is supposed to be fitting the period of high PV and WT energy generation to increase direct energy utilization.

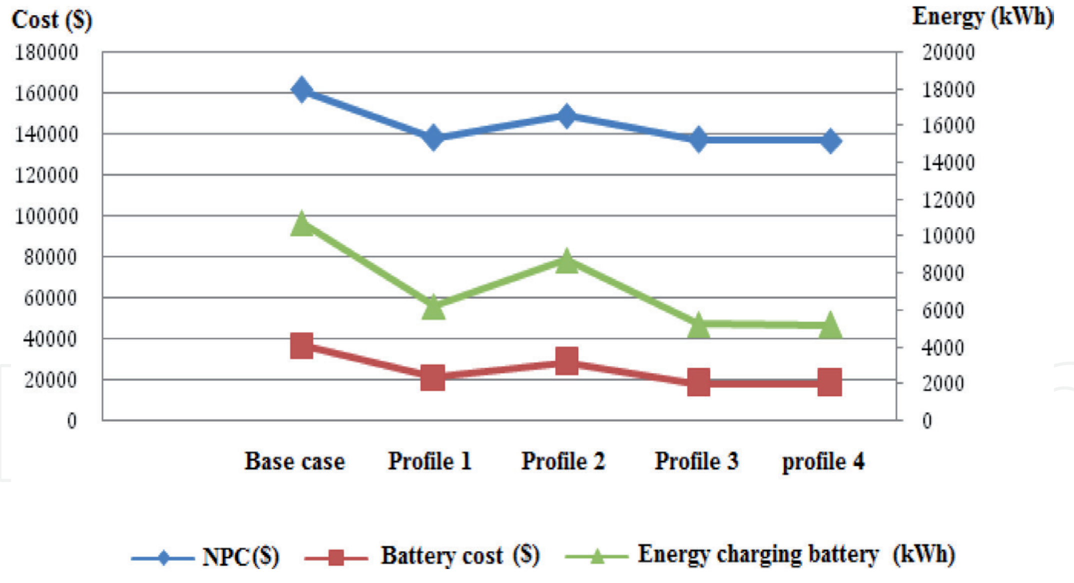

Figure 8.
Effect of suggested load profiles on NPC, battery cost, and energy battery charging.

Case no.	NPC ($)	COE ($/kWh)	PV cost ($)	WT cost ($)	Battery cost ($)
Base case	162,034	0.17	37,282	27,246	36,940
Profile 1	138,249	0.15	34,545	27,246	21,274
Profile 2	149,266	0.16	31,808	27,246	28,692
Profile 3	137,694	0.15	30,440	27,246	18,444
Profile 4	137,011	0.15	30,440	27,246	18,451

Table 3.
Cost results of the suggested load profiles ($).

Case no.	NPC ($)	Charge battery (kWh/year)	Excess energy (kWh/year)
Base case	162,034	10,768	8278
Profile 1	138,249	6231	6312
Profile 2	149,266	8768	4544
Profile 3	137,694	5294	3590
Profile 4	137,011	5241	3665

Table 4.
Results of the suggested load profiles.

The simulated optimization results of base case and the suggested four load profiles are exhibited in **Tables 3** and **4**.

It is noticed from the summarized results in the above tables that load profile 4 has the lowest NPC and COE (137,011$ and 0.15 $/kWh) among the four suggested profiles in addition to minimum value of energy charging the batteries (5241 kWh/year). The suggested load profiles also demonstrate the effect of decreasing the energy charging the batteries on the NPC as illustrated in **Figure 8**.

It is clear from **Figure 8** that the lowest battery charging energy is that of load profile 4 (5241 kWh) which is the case of lowest NPC configuration (137,011 $). **Table 5** exhibits the energy utilization, battery charging energy, and energy loss as a percentage of the total energy. It also exhibits battery cost as a percentage of the total energy system costs.

Case no.	Utilization (%)	Energy charging batteries (%)	Energy loss (%)	Battery cost (%)
Base case	55	27	22	22.8
Profile 1	66	16	18	15.4
Profile 2	65	22	13	19.2
Profile 3	73	13	14	13.4
Profile 4	73	13	14	13.4

Table 5.
Load profiles' results (percentages).

The above tables showed that decreasing excess energy and energy charging batteries reduced NPC cost. Increased utilization of the location resources is achieved through fitting the peaks of demanded load with the periods of high power generation which affected energy components, reducing generation and storage components' sizes.

9. Conclusions and recommendations

The optimization results for HRES under study, considered as the base case, are NPC is $162,034, COE is 0.17 $/kWh, and the unmet load (energy shortage) is 1.3% of the total required energy, while the renewable fraction is about 75%. However, this optimum configuration showed high values of energy charging batteries (which means higher battery bank capacity) and excess energy which represented 21 and 16%, respectively. At the same time, the total load that is directly supplied by energy sources was only 55% of total generated energy. This indicated that the load profile does not match the renewably generated energy; hence, different load scenarios were investigated. The simulation results of the best reached load pattern, referred to as "load profile 4," are as follows:

- Maximizing direct use of renewable generated energy causes reduction in system component sizes. The results showed that "load profile 4" has the lowest NPC and COE values (137,011 $ and 0.15 $/kWh) and minimum energy charging batteries (5241 kWh/year), which suggests that NPC and COE are directly proportional to energy charging battery.

- Managing load pattern to reach the best fitted profile has decreased NPC by 15.4%, charging energy battery by 51.3%, the cost of batteries by 50%, COE by 11.7%, and the excess energy by 55.7%, while the utilization of the energy sources is increased by 18%, compared to the base case configuration.

In short, "load profile 4" caused significant improvement on the following parameters:

- NPC has decreased by 15.4%.

- Battery charging energy has decreased by 51.3%.

- The cost of batteries has decreased by 50%.

- The cost of energy has decreased by 11.7%.

- The excess energy has decreased by 55.7%.

- The utilization of the energy sources is increased by 18%.

Taking environmental impacts of CO_2 into consideration will further decrease the cost of system generated energy.

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References

[1] Patel MR. Wind and Solar Power Systems. CRC Press LLC; 1999. ISBN: 0-8493-1605-7. Available from: www.crcpress.com

[2] Badr MA, ElKordy MN, Mohib AN, Ibrahim MM. Cost analysis of hybrid wind energy generating system considering CO_2 emissions. International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering. 2016;**10**(5)

[3] Linear-Programming Applications. Daniel Mackie/Stone; 1989. Web Chapter B. Available from: http://www.swlearning.com/economics/mcguigan/mcguigan9e/web_chapter_b.pdf

[4] Antoniou A, Lu W-S. Practical Optimization: Algorithms and Engineering Applications. Springer; 2012

[5] Waqas S. Development of an optimization algorithm for auto sizing capacity of renewable and low carbon energy systems [MSc]. Department of Mechanical Engineering, University of Strathclyde Engineering; 2011

[6] Connolly D. A review of computer tools for analyzing the integration of renewable energy into various energy systems. Applied Energy. 2010;**87**:1059-1082

[7] Dufo-López R. User Manual of iHOGA. 2016. Available from: www.unizar.es/manual delusuario

[8] Dufo-López R, Pérez-Cebollada E, Bernal-Agustín JL, Martínez-Ruiz I. Optimization of energy supply at off-grid healthcare facilities using Monte Carlo simulation. Energy Conversion and Management. 2016;**113**:321-330

[9] Fadaeenejad M, Radzi MAM, AbKadir MZA, Hizam H. Assessment of hybrid renewable power sources for rural electrification in Malaysia. Renewable and Sustainable Energy Reviews. 2014;**30**:299-305

[10] Gudelj A, Krčum M. Simulation and optimization of independent renewable energy hybrid system. Transactions on Maritime Science. 2013;**1**:28-35

[11] Dursun B et al. Techno-economic evaluation of a hybrid PV-wind power generation system. International Journal of Green Energy. 2013;**10**:117-136

[12] Rahman M, Khan MM-U-H, Ullah MA, Zhang X, Kumar A. A hybrid renewable energy system for a North American off-grid community. Energy. **97**:151-160

[13] Ngan MS, Tan CW. Assessment of economic viability for PV/wind/diesel hybrid energy system in southern peninsular Malaysia. Renewable and Sustainable Energy Reviews. 2012;**16**:634-647

[14] Badr MA, Mohib AN, Ibrahim MM. Small wind turbine hybrid system for remote application: Egyptian case study. International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering. 2014;**8**(9)

[15] Khattab NM, Badr MA, Maalawi KY, El Shenawy ET, El Ghetany HH, Ibrahim MM. Hybrid renewable energy system for water desalination: A case study for small green house hydroponic cultivation in Egypt. ARPN Journal of Engineering and Applied Sciences. 2016;**11**(21)

[16] Thevenard D, Leng G, Martel S. The RETScreen model for assessing potential PV projects. In: Conference Record of the Twenty-Eighth IEEE Photovoltaic Specialists Conference 2000; AK: IEEE. 2000. pp. 1626-1629

[17] Harder E, Gibson JMD. The costs and benefits of large-scale solar photovoltaic power production in Abu Dhabi, United Arab Emirates. Renewable Energy. 2011;**36**:789-796

[18] Green HJ, Manwell JF. HYBRID2: A Versatile Model of the Performance of Hybrid Power Systems. USA: National Renewable Energy Laboratory; 1995. pp. 1-12

[19] Beckman WA et al. TRNSYS: The most complete solar energy system modeling and simulation software. Renewable Energy. 1994;**5**(1):486-488

[20] Erdinc O, Uzunoglu M. Optimum design of hybrid renewable energy systems: Overview of different approaches. Renewable and Sustainable Energy Reviews. 2012;**16**:1412-1425

[21] Hossaina M, Mekhilefa S, Olatomiwa L. Performance evaluation of a stand-alone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia. Sustainable Cities and Society. 2017;**28**:358-366

[22] Olatomiwa L, Mekhilef S, Ismail MS, Moghavvemi M. Energy management strategies in hybrid renewable energy systems: A review. Renewable and Sustainable Energy Reviews. 2016;**62**:821-835

[23] Fouad MA, Badr MA, Ibrahim MM. Economic evaluation of micro-grid system (on/off grid): Egyptian case study. International Journal of Scientific and Engineering Research. 2017;**8**(2):17-24

[24] Bekele G. Feasibility study for a standalone solar-wind-based hybrid energy system for application in Ethiopia. Applied Energy. 2010;**87**:487-495

[25] Das HS, Dey A, Wei TC, Yatim AHM. Feasibility analysis of standalone PV/wind/battery hybrid energy system for rural Bangladesh. International Journal of Renewable Energy Research. 2016;**6**:402-412

[26] Alam MS, Gao DW. Modeling and analysis of wind/PV/fuel cell hybrid power system in HOMER. In: Second IEEE Conference on Industrial Electronics and Applications. 2007. pp. 1594-1599

[27] Ajao KR, Oladosu OA, Popoola OT. Using HOMER power optimization software for cost benefit analysis of hybrid-solar power generation relative to utility cost in Nigeria. International Journal of Research and Reviews in Applied Sciences. 2011;7:96-102

[28] Fulzele JB, Daigavane MB. Simulation and optimization of hybrid PV-wind renewable energy system. In: 3rd International Conference on Electrical, Electronics, Engineering Trends, Communication, Optimization and Sciences (EEECOS). 2016. pp. 159-164

[29] Tawfik TM, Badr MA, El-Kady EY, Abdellatif OE. Optimization and energy management of hybrid standalone energy system: A case study. Renewable Energy Focus. 2018;**25**:48-56

[30] NASA Surface meteorology and Solar Energy: RETScreen Data. Available from: https://eosweb.larc.nasa.gov/cgi-bin/sse/retscreen.cgi?email=&step=1&lat=30.6667&lon=30.0667&submit=Submit

[31] Yazdanpanah M-A. Modeling and sizing optimization of hybrid photovoltaic/wind power generation system. Journal of Industrial Engineering International. 2014:10-49