Economic-environmental evaluation of using green energy resources with considering pollution limitations

Mohammad Mahdi Borhan Elmi[1], Hamed Lotfi[2], Amir Hossein Lotfi[3]
1-Istanbul Aydin University, Istanbul, Turkiye
2- Islamic Azad University, Bojnourd branch, Bojnourd, Iran
3- Islamic Azad University, Mashhad branch, Mashhad, Iran

Abstract
Renewable energy resources such as wind and solar have been attracting much attention as green resources of energy in recent decades. This is due not only to the decrease in fossil fuel consumption but also to alleviate environmental pollution and global warming problems. The aim of this research is the economic-environmental evaluation of using green energy resources instead of operating fossil fuels-based generators. In this regard, a standalone hybrid system (solar panels/wind turbines/diesel generators/batteries) are used to supply the demand of 760 consumers. The 9-bus IEEE network consists of 10 load points with maximum demand 960 MW and 5 transmission lines is considered and grey wolf algorithm is used to determine the optimal size of the green resources. In this paper, in order to evaluate the performance of the proposed approach, 4 different scenarios have been designed. According to the obtained results, for every 10000 kg/yr reduction in CO_2 emissions, $12,000 is added to the cost of supplying the required demand.

Keywords: Green Energy, Hybrid System, Cost Optimization, Pollution Reduction, Grey Wolf Algorithm.

Introduction

In remote areas that do not have access to the main grid, electric energy is usually provided through diesel generators. This type of electric energy production requires fossil fuel also pollutes the surrounding environment. Therefore, the efforts of operators are to use green resources to provide electric power in a clean and environmental friendly manner. Meanwhile, using a renewable resources for a long period of time is not cost-effective due to the high cost of investment and the provision of sufficient capacity from the storage system [1]. To overcome such a challenge, green energy sources such as wind and solar energy can be used in combination with a suitable energy storage systems. In this paper, a technique for designing the optimal size of a hybrid system consisting of a solar panel/wind turbine/energy storage system and generator is presented, which simultaneously minimizes the cost of energy production and reduces emissions as much as possible. In this regard, the intensity of solar irradiations, the temperature of the studied environment, and the wind speed of a region called Gandon in the northwest coast of Senegal have been used [2].

Fuel cells in combination with electrolyzer (to produce hydrogen) and hydrogen storage tanks are considered as sources for energy storage. According to recent studies, it is better to use batteries from an economic point of view (Table 1). The main reason for this is the relatively low efficiency of the fuel cell compared to the battery. In fact, if the fuel cell system with the electrolyzer does not have any investment costs, the use of the battery is still economically. In fact, this research confirms that significant improvements are needed for both fuel cells and electrolyzer devices to be able to compete economically with other green energy resources.

Table 1- Pros & cons of different storage systems [3]

Storage system	Advantages	Disadvantages	Total Cost ($/kWh)	Annual Cost ($)
Fuel cell/ Electrolyzer	The possibility of hydrogen gas production	Less efficiency	0.70	11930
	Environmentally friendly Low cost of size increasing	Higher cost		
Battery	Low efficiency	Loss of energy when the storage are empty Need for charging/ replacing	0.37	6304
	Lower cost	Producing unti-environmental effects High cost of capacity increasing		

Literature Review

Moving towards creating a green economy is a key element to achieve a sustainable economic and social development. In fact, environmental protection has a direct relationship with a safer, healthier work environment and providing all people with proper working conditions [4]. According to studies conducted by various organizations, green energy sources create more employment compared to fossil sources. Table 2 shows the amount of employment generated by new energy sources during the period of construction and operation. Assuming an annual operation of 7,200 hours, for each MW biomass power plant, 33.75 and 101.25 people will be employed during the construction and operation period of 20 years [5]. Currently, 62 countries use biomass fuel in electricity production, with the largest share of 26% in U.S., 15% in Germany, and 7% in Brazil and Japan [6]. Green jobs, especially in the field of renewable energy, change the economy to a more efficient one, with less pollution and more competitive power. Investments and policies of the global markets are changing towards the field of renewable energy and it is predicted that more than 12 million people will work in the field of biomass by 2050 [7]. According to the World Energy Council’s report (2019) on the future of energy, there are 3 scenarios for the 2040 horizon. In the first scenario, the world is with high economic growth along with digitization and finding the importance of entrepreneurship, which can accelerate the development of renewable energies at the global and local level. In the second scenario, the governments at the global level choose coordinated and long-term policies to solve the challenges related to climate change at the national level and move towards a sustainable economic and social development program, which can lead to the growth of energy sources. In the third scenario, we are facing a fragmented world with introverted policies, less cooperation and economic growth, and the emergence of populist leaders, which creates an uncertainty in the international outlook, which in this scenario pays less attention to sustainability and renewable energy issues [9]. The authors of [10] investigate South Korea's advanced scenarios for transitioning to a sustainable energy system until the horizon of 2040 and finally present 4 scenarios, which are based on the difference in the level of energy consumption and the share of renewable energies. In the first scenario, policies adopted by the government and advances in technology will reduce the level of energy consumption in South Korea. In the second and third scenarios, renewable energies will replace coal and nuclear power plants over time and constitute 45 and 48 percent of the primary energy supply, respectively, and finally, in the fourth scenario, a future with 100 percent renewable energy will be shown. shows that South Korea is going to eliminate carbon until the horizon of 2040.

Table 2- The amount of employment in different fields of energy [8]

Type of Energy	Construction period (No. of person/kW)	Operation period (year)
Wind	14	11
Solar	20	20
Biomass	9	27

The authors of [11], by examining two eastern provinces of China and considering challenges such as high energy consumption, increased carbon dioxide emissions, reduced coal reserves and low productivity, presented 3 scenarios up to the horizon of 2050 to supply the electricity needed by these two provinces. In the first scenario, the current policies of the government are still followed. In the second scenario, natural gas and nuclear power are used to supply the required electricity, and in the third scenario, these provinces supply their electricity through renewable energy and electricity imports. In [12], stating that the energy policies published by the South Korean government emphasize that by 2030, about 20% of the country's energy needs to be provided by renewable energies and from the number of coal and nuclear power plants. also gradually decrease, they present 4 potential scenarios of renewable energies until 2030. In the first scenario, the activities are followed in a normal and current way. In the first and second scenario, solar and wind energy will grow respectively, and in the fourth scenario, solar and wind energy will grow together, which can meet the government's demands from the economic point of view and the reduction of carbon dioxide emissions in the long term. In its report on the future of energy in Scotland, the Scottish Electricity Network Company presents 3 scenarios up to the horizon of 2030. In the first scenario, Scottish consumers are in favor of reducing carbon dioxide emissions, and this issue increases their use of renewable energy and contributes to the reduction of carbon dioxide emissions at the national level. The focus is on investment in mega projects and policies to stimulate the development of renewable technologies. In the second scenario, Scottish consumers and businesses are affected by cost reductions as well as carbon dioxide emissions reductions and invest in decentralized small-scale electricity generation to reduce their costs. Finally, in the third scenario, Scottish consumers are less willing to invest in renewable technologies and small-scale electricity generation, but the issue of energy efficiency is still a concern of the government. In this scenario, the focus is on reducing costs and reducing carbon dioxide emissions is a secondary goal [13].

Gray Wolf Optimization

Gray wolves are originally a species of Canadian wolves that live in groups. The leaders of the group are called Alpha, Beta and Gamma. Alpha is responsible for making decisions about hunting, where to sleep, and when to wake up. Decisions made by Alpha are dictated to all members of the group. Alpha wolves are only allowed to mate with wolves within their pack. The important point is that they are not necessarily the strongest members of their group, but they have the best management power among other wolves. This shows that for the group of wolves, organization and management order is much more important than strength. At the second level of the hierarchy of gray wolves, the beta group is placed. This category includes submissive wolves who help the alpha wolf in making decisions or other social activities. The wolf belonging to this category is the best option to replace the alpha wolf in the absence or when he is old.

The lowest category belongs to the Omega group. This group of wolves always follows the wolves of the group above them and they are the last ones who are allowed to eat food. This group helps all members of the group and maintains the established dominance structure in the group. In some groups, it has been seen that these wolves protect children. If a wolf is not an alpha, beta or omega, it is called a dependent wolf or a delta wolf. Delta wolves must obey the orders of alpha and beta wolves, but they have control over omega wolves. Surveillance, guarding, hunting and care are among the duties of this category. In order to mathematically model the dominance hierarchy of gray wolf optimization (GWO) algorithm, the best solution obtained at each stage is considered as the alpha wolf. In the following, the second and third best answers are assumed to be equal to beta and delta, respectively. The rest of the answers in the studied population are classified under the omega group. In the GWO algorithm, optimization is done by guiding alpha, beta and delta wolves. In other words, the other wolves follow these three wolves. In line with the mathematical modeling of the behavior of wolves, equations 1 to 4 are used [14].

$$\mathbf{D} = \left|\mathbf{C}.\mathbf{X_p} - \mathbf{X(t)}\right| \quad (1)$$

$$\mathbf{X(t+1)} = \mathbf{X_p(t)} - \mathbf{A}.\mathbf{D} \quad (2)$$

$$\mathbf{A} = 2\,\mathbf{a}\,\boldsymbol{r_1} - \boldsymbol{a} \quad (3)$$

$C = 2\, \boldsymbol{r_2}$ (4)

The components of the vector 'a ' are linearly reduced from the value 2 to 0 during the repetition of the algorithm, and the vectors r_1 and r_2 are random vectors between the values 0 to 1. GWO has the ability to detect the location of prey and surround it. The hunt is usually led by the alpha. Beta and delta wolves may occasionally participate in hunting. However, in the abstract space used in our problem, there is no idea about the optimal position (prey). In order to mathematically model the hunting behavior of GWO, assumed that alpha, beta, and delta have better knowledge of prey location. Therefore, three candidates positions in each step are considered and other positions are regulated according to them. The updating procedure of positions are shown in Figure 1. It can be seen that the final position is in a random position according to the position of the alpha, beta and delta circles. In fact, these three wolves have guessed the location of the prey and the rest of the wolves update their position randomly based on this position. The new position of each wolf is obtained based on the equation 5 [14].

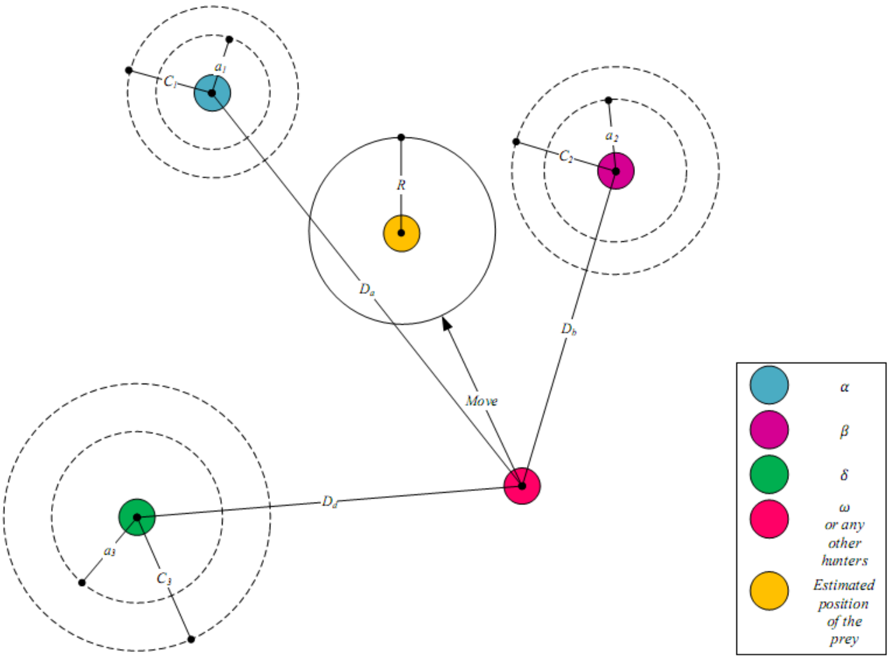

Figure (1) Updating procedure in GWO [14]

$$\mathbf{D_\alpha = |C_1.X_\alpha - X|;\;\; D_\beta = |C_2.X_\beta - X|;\;\; D_\delta = |C_3.X_\delta - X|;} \quad (5)$$

$$\mathbf{X_1 = X_\alpha - A_1.(D_\alpha)} \quad (6)$$

$$\mathbf{X_2 = X_\beta - A_2.(D_\beta)} \quad (7)$$

$$\mathbf{X_3 = X_\delta - A_3.(D_\delta)} \quad (8)$$

$$\mathbf{X(t+1)} = \frac{\mathbf{X_1 + X_2 + X_3}}{\mathbf{3}} \quad (9)$$

Main steps of GWO

In this algorithm, the search process begins with the generation of an initial population of gray wolves, which are considered as candidate solutions in the search space of the algorithm. During the iteration process of the algorithm, alpha, beta and delta wolves estimate the possible position of the prey. All other wolves update their positions relative to the their positions. Finally, upon reaching the termination criteria of the algorithm, alpha wolf is selected as the most optimal solution. In this situation, the main steps of the gray wolf algorithm are described as follows:

1. Initial population of gray wolves
2. Determining the initial values for coefficients a, A and C
3. Considering the best three solutions as alpha, beta and delta
4. Updating the wolves' position according to leaders (equation 2)
5. Updating coefficients A and C (equation 3)
6. Calculate the fitness of all members in new situation
7. Updating the location of alpha, beta and delta wolves (equations 5 to 8)
8. Determining the location of prey (equation 9)
9. If the termination criteria not achieved, go to step 4

Problem Formulation

The proposed hybrid system consists of wind turbine, solar array, diesel generator and battery. The solar array and the wind turbine work together to provide the electrical power required by the load. Whenever the amount of their produced energy is excess, this energy is transferred to the storage system. When the solar array and wind turbine are not able to supply the demand, the energy stored in the battery is used to compensate. If conditions are provided that not only the renewable resources are not able to meet the demand but also the battery do not have the required charge, then the diesel generator will be used. The objective function is defined according to equation 10. This function consists of two parts. The first part shows the levelized cost of energy (LCE) which is obtained by calculating all current costs on the total energy generated in each year. The second part includes the amount of fuel consumption (FCon) for the diesel generator, which is related to the releasing of CO_2 pollution for the environment. In equation 10, weight coefficients $\mathbf{W_1}$ and $\mathbf{W_2}$ are used which show the importance of present costs and emitted pollution, respectively. In other words, the scheduler can change the weight coefficients according to his desires according to the importance of each of the above items. In equation 11, levelized cost is calculated. In equation 11, the total cost of the system is achieved by calculating the total cost of investment, maintenance, and replace the equipments. For levelization, this calculated cost is divided by the total annual production energy. In the designed objective function, there is a part that shows the contribution of the environmental pollution produced due to the use of diesel generators. The pollution according to the consumption of fossil fuels (FCon) is calculated through the equation 12.

$$\mathbf{Min\ O.F = W_1.LCE + W_2.FCon} \quad (10)$$

$$\mathbf{LCE} = \frac{\mathbf{J(x)}}{\mathbf{E\_annual}} \quad (11)$$

$$\mathbf{FCon} = \mathbf{A.P_{NG} + B.P_{OG}} \quad (12)$$

In this paper, renewable sources such as photovoltaic array and wind turbines are used to supply the demand. In equation 13, the production power of solar array is stated based on its quantities. In equation 14, the average output power of the wind turbine is calculated. The amount of solar regulator’s output current is calculated as equation 15.

$$\mathbf{P_{pv} = V_{oc}.I_{sc}.FF} \quad (13)$$

$$\mathbf{P_{wind}} = \mathbf{P_r}.\left\{\frac{\exp\left[-\left(\frac{V_{Cin}}{A}\right)^k\right] - \exp\left[-\left(\frac{V_r}{A}\right)^k\right]}{\left(\frac{V_r}{A}\right)^k - \left(\frac{V_{Cin}}{A}\right)^k} - \exp\left[-\left(\frac{V_{Cou}}{A}\right)^k\right]\right\} \quad (14)$$

$$\mathbf{I_{rg}} = \frac{\mathbf{N_{pv}.P_{pv}}}{\mathbf{N_{pvs}.\eta_{rg}.U}} \quad (15)$$

System Characteristics

The under studied microgrid has 9 buses and 10 load points (Figure 1) [14]. Information of load points as well as the number of customers correspond to each bus are listed in Table 3. In this microgrid, diesel generator, energy storage system, photovoltaic array and wind turbine are used as green energy equipments for power generation and storage, and the information about green resources are shown in Table 4 and Table 5. If we consider just an economic point of view, the optimal way to supply all the required demand is using diesel generators, but this causes the emission of GHG gases, which are harmful for the environment.

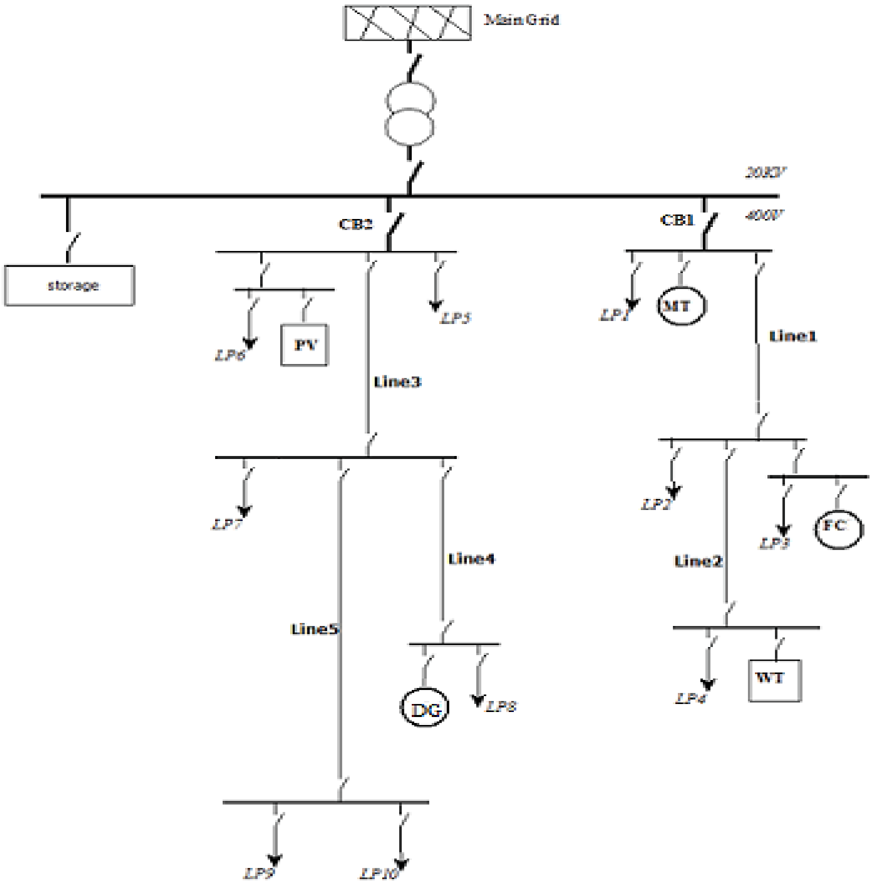

Figure (2) Scehmatis of under studied Microgrid [15]

Table 3- Characteristics of load points [15]

Load Point No.	Min Power (MW)	Max Power (MW)	No. of Customers
1	100	135	120
2	120	160	140
3	15	60	35
4	10	45	28
5	75	95	85
6	25	65	45
7	20	70	45
8	90	140	115
9	85	130	107
10	15	60	40

The profile of wind pattern of the area is shown in Figure 3. As can be seen, there is a relatively good wind blowing, so that more than 40% of the blown winds have a speed of more than 10(m/s). For solar irradiations, the intensity of irradiation in the middle of the day is slightly more than 700 W/m^2, which indicates that there is not strong possibility for solar irradiations in this area.

Table 4- Characteristics of wind turbine, solar module and battery [2]

Wind Turbine		Solar Module		Battery	
Cut-in Speed (m/s)	2.5	Rated Voltage (V)	12	Capacity (Ah)	200
Rated Speed (m/s)	14	Rated Power (W)	150		
Cut-off Speed (m/s)	25	Short Circuit Current (A)	8.4	Rated Voltage (V)	12
Rated Power (W)	5600	Open Circuit Voltage (V)	21.6		
Output Voltage	48	Efficiency Coefficient	0.74	Cost ($)	416
Cost ($)	8870	Cost ($)	900		

Table 5- Characteristics of regulator and inverter [2]

Regulator		Inverter	
Rated Current (A)	30	Rated Voltage (V)	48
Rated Voltage (V)	48	Rated Power (W)	3500
Cost ($)	230	Short Circuit Current (A)	2799

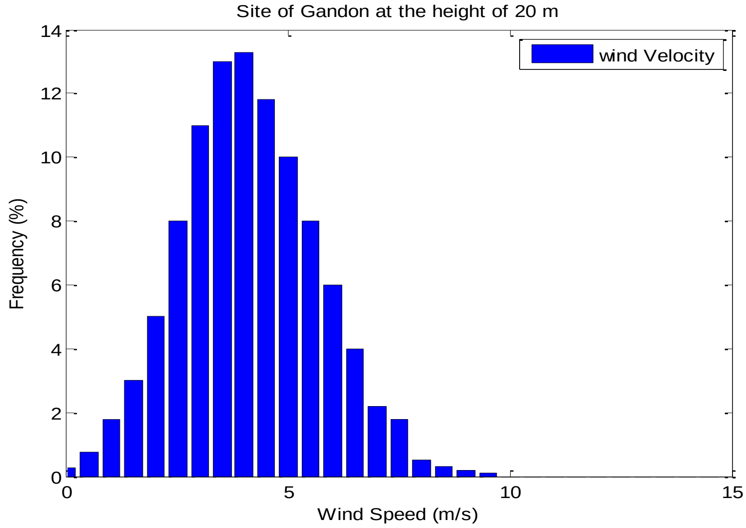

Figure (3) Wind pattern in the area [15]

Simulation Results

The Min. and Max. demand required by consumers are assumed to be 555 MW and 960 MW, respectively. These green resources must be supply the demand for 760 consumers. To implement the GWO, an initial population of states has been considered. In this regard, 50 different combinations based on a number of solar panels and wind turbines have been considered to provide the desired power. It should be noted that the number of solar panels and wind turbines in each case is considered to be able to provide the required power of total demand, and after that the capacity of inverters and regulators are determined. In fact, the variable number of inverters and regulators have a direct relationship to the number of solar panels and wind turbines and is considered as a kind of dependent variables. Diesel generators are also used to provide power for situations where green sources are not able to provide the required power.

In this simulation, four scenarios are considered. In the first scenario, only diesel generators were used to supply the required demand, and in the second, third and fourth scenarios, diesel generators were used together with renewable sources to supply the total demand. The differences of scenarios 2, 3, and 4 are due to the limit of their emissions, which are set at 10000, 20000, and 40000 $kgCo^2$, respectively. Since the supply of power by diesel generators is the most economical method possible according to the considered costs, therefore, in each scenario, the maximum number of possible diesel generators is determined based on the emission requirement. Therefore, the number of diesel generator units is specified according to this status.

Scenario 1: Without green resources

Some of appliances that have a fixed pattern of power consumption which not capable to participate in demand response programs. In this case, it is only assumed that diesel generators will be used to generate the required demand. The required load is considered equal to 94 kWh. In Table 5, the amount of initial cost as well as the amount of produced pollution are described in Table 6. In fact, in this part, all of the demand is provided by using diesel generators, and green resources do not play any role in power generation. The initial investment cost is estimated between 25.000$ to 29.000$. In other side, the amount of pollution is estimated between 73.000 $kgCo^2$ to 74 $kgCo^2$.

The number of diesel generators used are 29, 23 and 20 for differebt kind of generators. Economically, this mode is considered as the best possible method, but as it can be seen from Table 6, it causes lots of pollution. With regarding the obtained results, using of diesel generator type 3 reduces the cost of project implementation, while it produces more pollution compared to other types of generators. In the following sections, it is assumed that there are pollution constraints on the generated energy, and hence the possibility of using this type of resources is limited.

Table 6- Cost vs. pollution of different diesel generators

Generator Type	Investment cost ($)	Total cost ($)	Pollution (kg. CO^2)
Type 1	29411	30881	73623
Type 2	28939	30386	73867
Type 3	25660	26943	74021

Scenario 2: Max. Pollution = 10000 $kgCo^2$

In this scenario, it is assumed that the maximum level of emission is 10000 $kgCo^2$. All of the scheduling of green resources organization and diesel generators is done in accordance to meet this constraint. The optimal results obtained by implementing this scenario is shown in Table 7. As it is clear from the results, if green resources are used, the amount of pollution can be kept at a certain level, although the total cost will increase between 2.5 to 3 times. In the area under study, because the solar irradiations have not proper quality, the proposed plan used more wind turbines.

Table 7- No. of green resources components

No. of Solar panels	23	No. of Regulators	2
No. of Wind turbines	13	No. of Inverters	21
No. of Batteries	30	No. of Diesel generators	6
Investment Cost ($)	78871	Total Cost ($)	82814

Scenario 3: Max. Pollution = 20000 kgCo^2

In this scenario, it is assumed that the max. level of emission is 20000 kgCo^2 (Table 8). In this situation, the amount of diesel generators is calculated as 12, and the total cost obtained in this part is 14,000 $ less than previous scenario. This issue is due to the relatively high cost of using green resources compared to diesel generators. With the advancement of technology and their widespread generation in the near future, this difference is expected to decrease.

Table 8- No. of green resources components

No. of Solar panels	3	No. of Regulators	1
No. of Wind turbines	10	No. of Inverters	17
No. of Batteries	21	No. of Diesel generators	12
Investment Cost ($)	65311	Total Cost ($)	68577

Scenario 4: Max. Pollution = 40.000 kgCo^2

In this part, it is assumed that the max. level o emission is 40.000 kgCo^2 (Table 9). In this situation, 24 diesel generators are used and the total cost is reduced by 36048 $. In this way, it is possible to obtain the optimal combination of these resources in different environmental conditions. In fact, this program is designed in such a way that address of pollution constraints is easily possible, and according to the possible rules established in the future, it is possible to design an optimal plan for using of green resources.

Table 9- No. of green resources components

No. of Solar panels	0	No. of Regulators	0
No. of Wind turbines	3	No. of Inverters	5
No. of Batteries	7	No. of Diesel generators	24
Investment Cost ($)	34332	Total Cost ($)	36048

Conclusion

In this project, two objective functions of the total cost of energy production and carbon dioxide emissions are studied simultaneously. In this regard, a self-reliance system consisting of solar panel / wind turbine / diesel generator / battery will be used to provide the required load and the gray wolf algorithm will be used to determine the optimal capacity of the resources used. This newly designed algorithm has proven its efficiency in various fields. In the second scenario, it is assumed that the maximum emission rate Pollution is at the level of 10,000 kg of carbon dioxide. All planning for the use of renewable sources and diesel generators is done in compliance with this condition. As it results from the results, if renewable sources are used, the amount of pollution can be kept at a certain level, but the total cost will increase between 2.5 and 3 times. In the third scenario, it is assumed that the maximum amount of emissions is at the level of 20,000 kg of carbon dioxide (in this case, the number of diesel generators used is equal to 12 and the total cost of this part is $ 14,000 less than before. In the last scenario, it is assumed that the maximum emission rate is 40,000 kg of carbon dioxide, in which case the number of diesel generators used is equal to 24 and the total cost is reduced by $ 36048.

List of Symbols

$\mathbf{C}$, $\mathbf{A}$	: Coefficient vectors
$\mathbf{X_p(t)}$	: Prey position vector at time step t
$\mathbf{X}$	: Gray wolf position vector
$\mathbf{J(x)}$	: Total system cost
E_annual	: Total amount of generated energy per year
$\mathbf{P_{NG}}$	: Nominal power of diesel generators
$\mathbf{P_{OG}}$	: Output power of diesel generators
$\mathbf{A}$, $\mathbf{B}$	: Constant coefficients of the fuel consumption in diesel generators
$\mathbf{V_{oc}}$	: Open circuit voltage
$\mathbf{I_{sc}}$	: Short circuit current
FF	: Load factor
$\mathbf{V_{Cin}}$	: Cut – in speed of wind turbine
$\mathbf{V_{Cou}}$	: Cut – out speed of wind turbine
$\mathbf{V_r}$	: Rated speed of wind turbine
$\mathbf{I_{rg}}$	: Current of regulator
$\mathbf{N_{pv}}$	: No. of solar panels
$\mathbf{P_{pv}}$	: Output power of solar array
$\boldsymbol{\eta_{rg}}$	: Efficiency of solar array
$\mathbf{N_{pvs}}$	: No. of series solar cells

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