Simulation of a Hybrid Power System Consisting of Wind Turbine, PV, Storage Battery and Diesel Generator: Design, Optimization and Economical Evaluation

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Abstract—**Hybrid power systems are based on renewable energy sources and especially on photovoltaic and wind energy systems. Software package is used to analyze measuring data for wind speed and solar radiation of two locations in Palestine (Ramallah and Nablus). Results of analysis illustrate that energy density available in wind for Ramallah site is about 2008 kWh/m^2.year, while it is 927 kWh/m^2.year for Nablus site. The daily average of solar radiation intensity on horizontal surface is about 5.4 kWh/m2 .day. A Matlab software package is used to simulate different scenarios of operation of the hybrid system by making energy balance calculations on an hourly basis for each of the 8760 hours in a year. This enable to choose the appropriate sizes of the different components for the most optimum scenario. The optimization is based on cost of generation. Results of the simulation illustrate that the most economic scenario is the scenario that uses a hybrid system mainly dependent on wind. Cost of energy (COE) in this scenario is 1.28 NIS/kWh(˜ 0.35 $/kWh). Other scenarios dependent on wind-diesel hybrid system, PV-diesel hybrid system, wind stand-alone system, PV stand-alone system, or diesel only, give results of COE greater than this value. It was concluded that none of the hybrid system scenarios analyzed could be justified to replace purchasing of electricity from the grid where the COE is 0.70 NIS/kWh(0.19 $/kWh).**

Keywords— **Hybrid Power System; Matlab; Wind Power; Photovoltaic; Energy Cost; CO2 Production ; Weibull Distribution; Diesel Generator**

I. INTRODUCTION

Hybrid power systems, which combine conventional and renewable power conversion systems, are the best solution for feeding the mini-grids and isolated loads in remote areas. Nowadays many applications in rural and urban areas use hybrid systems. Many managers of isolated loads try to adopt this kind of technology because of the benefits which can be received in comparison with a single renewable system.

For the Palestinian case, the daily average of solar radiation intensity on horizontal surface is about 5.4 kWh/m^2.day, while the total annual sunshine hours amounts to about 3000 [1]. These figures are relatively high and very encouraging to use PV generators for electrification of certain loads as it has been worldwide successfully used.

The annual average of wind velocity at different places in Palestine is about 3 m/s which makes the utilization of wind energy converters surely un feasible in such places . In other places it exceeds this number and reaches up to 5.5 m/s (Al-Mazra'a Al-sharqiyah/Ramallah is an example and it is the case under study in this paper) which makes it feasible to be used to operate a wind turbine. At Nablus, the annual average of wind velocity is about 4.5 m/s. Nablus site is also considered in this study for comparison with Ramallah site [2].

II. BLOCK DIAGRAM OF A HYBRID SYSTEM

The configuration used to be evaluated in this paper has a DC bus which combines the DC output of the PV module, the DC output of the wind turbine, and the battery bank. The AC bus of this configuration combines the output of the bidirectional inverter, the output of the back-up diesel generator and the load. This parallel configuration requires no switching of the AC load supply while maintaining flexibility of energy source, but the bidirectional power inverter shall be chosen to deal with this mode of operation. The block diagram of this configuration is illustrated in Figure1.

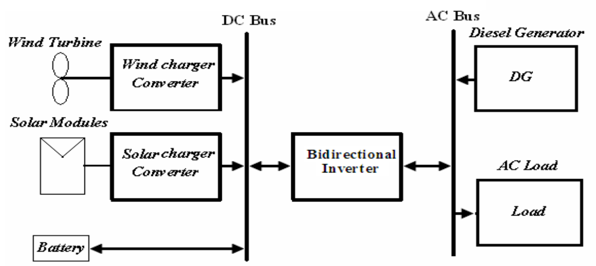

Fig. 1 Block diagram of the hybrid system.

I. WIND SPEED DATA ANALYSIS

A. Power in Wind

The power (P) available in the wind in watts is equal to:

$$P = \frac{1}{2} \times \rho \times A \times V^3 \qquad (1)$$

where ρ is density of air (kg / m^3), A is captured area of wind turbine in (m^2) and V is wind speed in (m/s).

As it is clear from the power relation, wind speed has a strong influence on power output.

The energy that a wind turbine will produce depends on both its power curve and the wind speed frequency distribution at the site. Wind speed frequency distribution is a graph showing the number of hours for which the wind blows at different wind speeds during a given period of time. Energy produced at any wind speed can be obtained by multiplying the number of hours of its duration by the corresponding turbine power at this wind speed obtained by the turbine's power curve. The total energy produced is calculated by summing the energy produced at all the wind speeds within the operating range of the turbine.

B. Effect of Height on Wind Speed

The height at which the wind speed is measured affects its measured value. As height increases the speed of wind increases.

So when calculating the output of wind generator, the measured data of average hourly wind speed must be converted to the corresponding values at the hub height. The most commonly used formula is power law, expressed as:

$$V/V_R = (Z/Z_R)^{\alpha} \qquad (2)$$

where V is wind speed at desired height (Z) ; V_R is wind speed at the reference height (Z_R); α is the ground surface friction coefficient, the one-seventh-power law ratio is used corresponds to most common surfaces [3].

C. Wind Speed Distribution

The distribution model most frequently used to model wind speed climatology is a two-parameter Weibull distribution because it is able to conform a wide variety of distribution shapes, from Gaussian to exponential. The Weibull probability density distribution function is given by .

$$F(v) = K \times \frac{v^{(K-1)}}{C^K} \times e^{-\left(\frac{v}{C}\right)^K} \qquad (3)$$

where K is the Weibull shape factor, it gives an indication about the variation of hourly average wind speed about the annual average, C is the Weibull scale factor [4].

Each site has its own K and C , both can be found if the average wind speed V and the available power in wind (flux) are calculated using the measured wind speed values.

D. Wind Data Calculations for Ramallah & Nablus Sites

Different wind measurements were carried for each month through the year 2006. The wind data obtained includes hourly average wind speeds for each hour in the month [2]. Calculations were performed on these data for each month to obtain the duration in hours for each 1 m/s speed range selected. The total wind speed range was divided into 1 m/s speed ranges taking the ranges: 0-1, 1-2, 2-3, 3-4, and so on.

For each month, average wind speed, percentage of occurrence of each wind speed, power density for each wind speed, Weibull values for each wind speed, energy available in the wind for each wind speed, and the total energy available in wind are calculated. Table 1 shows the average wind speed for each month and the corresponding energy available in the wind for Ramallah site. Similar analysis was done for Nablus site, where the results are shown in Table 2.

TABLE 1

AVERAGE WIND SPEED FOR EACH MONTH/RAMALLAH.

Speed range (m/s)	Duration yearly (hours)	Energy available in wind(kWh/m²) Using data	Energy available in wind(kWh/m²) Using Weibull
0-1	733.68	0.03	0.06
1-2	376.64	2.08	0.77
2-3	1105.78	12.90	10.45
3-4	1786.15	37.70	46.33
4-5	1802.06	73.62	99.35
5-6	1285.92	110.12	129.44
6-7	788.24	135.01	130.97
7-8	440.14	141.05	112.34
8-9	205.65	128.66	76.41
9-10	101.65	104.17	52.73
10-11	55.81	75.74	39.09
11-12	25.93	49.87	23.86
12-13	9.67	29.94	11.42
13-14	5.17	16.47	7.69
14-15	2.83	8.33	5.23
15-16	8.17	3.89	18.40
16-17	3.83	1.68	10.42
17-18	0.83	0.67	2.70
18-19	0.67	0.25	2.55
19-20	0.50	0.09	2.24
20-21	1.00	0.03	5.21
21-22	7.83	0.01	47.10
22-23	0.67	0.00	4.59
23-24	11.17	0.00	87.68
Sum	8760	932.33	927.02

TABLE 1

YEARLY WIND SPEED CALCULATIONS/NABLUS SITE

Month	Average wind speed	Energy available in wind(kWh/m²) Using data	Energy available in wind(kWh/m²) Using Weibull
1	6.74	361.71	234.71
2	6.58	229.85	164.44
3	6.49	283.66	173.04
4	6.75	254.52	252.30
5	4.90	100.23	200.06
6	5.58	132.88	162.76
7	5.83	145.49	200.49
8	5.33	104.14	126.30
9	4.90	80.90	119.10
10	5.21	96.46	129.33
11	3.90	125.41	145.16
12	4.52	92.76	121.54
Sum		2008.02	2029.25

Figure 2 shows a graphical presentation of hourly duration for different ranges of wind speed.

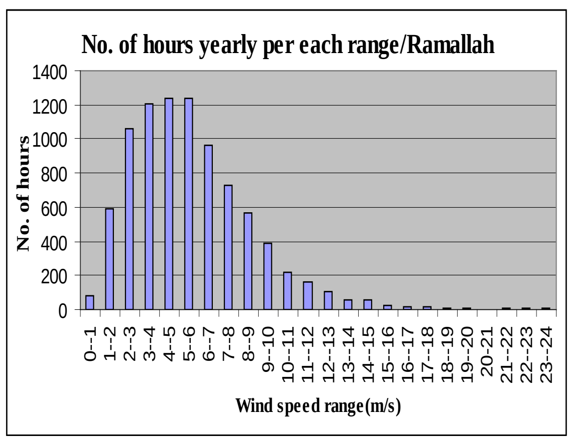

Fig. 2 Number of hours per year for each wind speed range/Ramallah.

III. SOLAR RADIATION DATA ANALYSIS

A. Photovoltaic Output Power

The output power from the PV module is affected by the variation of cell temperature and variation of incident solar radiation. The maximum power output from the PV cell can be calculated using the following equation.

$$P_{out\text{-}pv} = P_{r\text{-}pv} \times (G/G_{ref}) \times [1 + KT\,(Tc - T_{ref})] \quad (4)$$

where Pout-pv is output power from the PV cell , Pr-pv is rated power at reference conditions , G is solar radiation (W/m²) , G_{ref} is solar radiation at reference conditions (G_{ref} =1000 W/ m²) ,Tc is cell temperature calculated using "(5)" , T_{ref} is cell temperature at reference conditions (T_{ref} = 25 °C) , KT is temperature coefficient of the maximum power (KT= - 3.7 $*10^{-3}$/ 1°C for mono and poly crystalline Si).

$$T_C = T_{amb} + 0.0256 \times G \quad (5)$$

Where, T_c and T_{amb} are the cell and ambient temperatures respectively [5].

B. Solar Radiation in Palestine

Solar radiation data during a year are very important and essential for design and sizing of PV power systems. Solar radiation measurements in addition to temperature measurements are necessary to calculate the output power of the PV system. Solar radiation and temperature measurements shall be available on hourly basis to be used by the simulation program for the evaluation process. Solar radiation and temperature measurements are complete and available for Nablus site. Table 3 presents the monthly average of daily solar radiation for Nablus site.

TABLE 2
SOLAR RADIATION IN NABLUS

Month	Monthly average solar radiation(kWh/m²-day)
1	2.89
2	3.25
3	5.23
4	6.25
5	7.56
6	8.25
7	8.17
8	8.10
9	6.30
10	4.70
11	3.56
12	2.84

IV. HYBRID SYSTEM COMPONENTS MODELING AND SIZING

It is important to determine the appropriate size of hybrid system components. The system should not be oversized (more expensive) or undersized (not capable to operate the load).

A. Load Profile

Load profile study and determination is the first step for design of any electric power system. Nature of loads and behavior of consumers are the parameters that determine the load profile. In Palestinian case most of loads are lighting fixtures, radio/TV, and domestic appliances (washing machines, fans, refrigerators, and others). The operation time and amount of these loads during the day represent the load profile as shown in Figure 3.

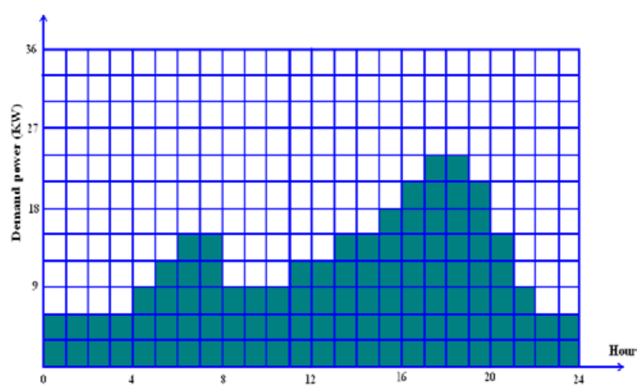

Fig. 3 A typical daily load curve.

B. Wind Turbine Modeling and Sizing

The power output of a wind turbine is determined by its power curve and the instantaneous wind speed at the site of installing this wind turbine. Based upon, a Mathematical model for the power curve of a wind turbine is given in "(6)" [6]:

$$P_W = \begin{cases} 0 & V < V_{ci} \\ a \times V^3 - b \times P_r & V_{ci} < V < V_r \\ P_r & V_r < V < V_{co} \\ 0 & V > V_{co} \end{cases} \quad (6)$$

where PW (in W/m²) is the output power generated by a wind turbine and Pr , V , Vci , Vr , Vco are rated power (W) , instantaneous, cut-in , rated and cut-out wind speeds in (m /s) respectively, while a and b are as follows:

$$a = \frac{P_r}{V_r^3 - V_{ci}^3} \qquad , b = \frac{V_{ci}^3}{V_r^3 - V_{ci}^3}$$

The real electrical power delivered is calculated as

$$P_{out} = P_w \times A_w \times \eta_G \qquad (7)$$

where Aw is the total swept area of the wind turbine in (m^2) , η_G is the electrical efficiency of the wind generator and any other electrical components connected to the generator.

C. PV Generator Modeling and Sizing

The total peak power of the PV generator required to supply certain load depends on load size , solar radiation , ambient temperature , power temperature coefficient , efficiencies of charge regulator and inverter as well as on the safety factor considered to compensate for all possible losses. This total peak power is obtained as follows:

$$P_{r-pv} = (E_L \times SF)/(\eta_R \times \eta_v \times PSH) \qquad (8)$$

where EL is the daily energy consumption in kWh , PSH is the peak sun hours (in Palestinian case PSH = 5.4) and as a figure it represents the yearly average of daily solar radiation intensity on horizontal surface in (kWh/m2 –day), η_R , η_V are efficiencies of charger regulator and inverter respectively and SF is the safety factor [1] .

V. STANDBY SOURCES IN THE HYBRID SYSTEM

A. Battery Sizing

The ampere-hour capacity (C_{Ah}) and watt-hour capacity (C_{Wh}) of a battery bank required to supply a load for a certain period (day) when an energy from renewable resources is not available can be specified as follows [1,5] :

$$C_{Wh} = (E_L \times AD)/(\eta_R \times \eta_B \times DOD) \qquad (9)$$

where AD : is the daily autonomy, DOD is depth of discharge.

It is obvious from Eq.9 that total capacity of the battery depends on daily autonomy which represents the number of days that battery will be capable to supply the load in case of shortage of the renewable sources.

B. Diesel Generator Ratings and Fuel Consumption

An approximation linear model for fuel consumption and its relation with rated power of the diesel generator and the actual power provided by this diesel generator is developed by Skarstein and Uhlen (1989) [7].

$$F = (0.246 \times P_{out}) + (0.08415 \times P_r) \qquad (10)$$

where F is fuel consumption (L/h), Pout is the actual operating output power (kW), Pr is the rated electric power of diesel generator (kW), 0.246 is an empirical factor and it is in (liters/kWh), and 0.08415 is also an empirical factor and it is in (liters/kWh).

VI. ECONOMIC EVALUATION OF THE HYBRID SYSTEM

The costs of a hybrid system include capital costs, operating costs, maintenance costs and replacement costs. At end of the life of the system, the system may have a salvage value. An economic analysis is done based on life cycle costing method, which accounts for all costs associated with the system over its life time, taking into account the value of money. Life cycle costing is used in the design of the hybrid system that will cost the least amount over its lifetime. Cost annuity (cost required to generate 1 kWh of energy) is an indication on the cost of the system so that the system with the least cost annuity is selected.

Comparison of different scenarios considered in the hybrid system analysis is based on calculating the cost of electricity production in ($/kWh) for each scenario. Cost of production (COE) includes all different costs: initial capital costs, recurring and nonrecurring costs due to operation, maintenance, repair, component replacement, and the fuel costs.COE is the ratio between the total annual cost and the total energy required by the load.

A. Simulation Approach and Power Flow Strategy

The system simulation is performed by considering the system reliability as 100%, so no interruption is assumed during operation of the system.

The developed optimization software enables to change the variables of the hybrid system model in terms of sizing and operation. In such a way the life cycle cost of the hybrid system while respecting the demand requirements is minimized.

In this approach the renewable energy sources (wind & PV) plus the energy stored in the battery are used to cover the demand. The diesel generator is switched on as a back-up source when the battery is discharged to a certain level. For each hour step the simulation program compares the required energy demand and the supplied energy, and according to the difference a decision to operate the diesel generator or to charge the battery or discharge it will be taken.

B. Special Inputs for the Case Study & Results Obtained

Different inputs concerning economical factors and wind turbine, PV system, diesel generator, battery, regulators and inverter characteristics and costs are inputs to simulation program.

Results of simulation program illustrate that the lowest cost of energy price is 1.28 NIS/kWh achieved at 50% PV contribution and 0.5 autonomy days(AD). Table 4 illustrates this result and other results for different values of PV contribution and different values of autonomy days.

A similar analysis for Nablus site illustrates that cost of energy is 1.4 NIS/kWh at 60% PV contribution and 0.5 autonomy days.

TABLE 3

COE (NIS/KWH) FOR THE WIND-PV HYBRID SYSTEM FOR DIFFERENT VALUES OF PV CONTRIBUTION AND AUTONOMY DAYS FOR RAMALLAH SITE.

AD	PV contribution (%)									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
0.1	1.45	1.39	1.38	1.42	1.47	1.53	1.60	1.67	1.74	1.81
0.2	1.44	1.36	1.33	1.37	1.42	1.48	1.54	1.62	1.68	1.76
0.3	1.45	1.38	1.35	1.34	1.37	1.41	1.47	1.53	1.60	1.68
0.4	1.48	1.38	1.32	1.30	1.29	1.30	1.35	1.41	1.49	1.56
0.5	1.47	1.39	1.34	1.29	1.28	1.30	1.33	1.40	1.47	1.54
0.6	1.49	1.42	1.34	1.32	1.29	1.31	1.35	1.41	1.49	1.56
0.7	1.56	1.44	1.38	1.33	1.30	1.32	1.38	1.44	1.52	1.59
0.8	1.59	1.45	1.40	1.33	1.34	1.35	1.41	1.47	1.55	1.62
0.9	1.60	1.49	1.40	1.36	1.37	1.38	1.44	1.51	1.59	1.67
1.0	1.61	1.52	1.43	1.38	1.39	1.42	1.48	1.55	1.63	1.70

C. Design Considerations of the Hybrid System and Different Costs

As stated in Table 5, rated power of wind turbine is 30 kW, rated power of the PV generator is 36.6 kW, rated capacity of the diesel generator is 24 kW, and the rated capacity of the battery bank is 240 kWh.

A 220 V DC is appropriate for the DC bus voltage which is the nominal voltage of the battery bank. The output of charge controller should be rated at this voltage level and the same applies for the bidirectional inverter .

TABLE 4

DESIGN DATA RESULTS OF WIND-PV HYBRID SYSTEM COMPONENTS FOR 50% PV CONTRIBUTION AND 0.5 AD FOR RAMALLAH SITE

Item	Description
Wind turbine rated power (kW)	30
PV panel size (kW)	36.6
Battery capacity (kWh)	240
Diesel generator capacity (kW)	24
Yearly load demand (kWh)	109500
Yearly energy generated by wind turbine (kWh)	92331
Yearly energy generated by PV panel (kWh)	73179.9
Yearly energy generated by diesel generator (kWh)	12492.2
Yearly dump energy (kWh)	54002

Diesel generator operating hours (hour)	521
Yearly fuel consumption (liter)	4124
COE (NIS/kWh)	1.28
LCC (NIS)	2256180
Yearly CO2 produced (kg)	10311

110*2 V cell lead acid batteries shall be connected in series to obtain this level of DC voltage at the DC bus. At 25 °C, this cell has a charging open circuit voltage equals to 2.4 V, so the maximum open circuit voltage for the bank is 264 V. The output of the charge controller and the DC voltage of the bidirectional converter have to match with this voltage. The Ampere-hour capacity (C_{Ah}) of the battery block, necessary to cover the load demand for AD=0.5 is C_{Ah}= 240*1000/220 = 1090 Ah. The battery cells shall be selected with this Ah rating.

A 2 V lead acid battery of 648Ah capacity (the nearest capacity found by battery manufacturers) can be used instead. In this case two parallel strings, each of 110 battery cells connected in series are necessary.

Mono-crystalline or poly-crystalline PV modules can be used to supply the load. If poly-crystalline PV modules of 54 W peak power are selected, the number of the necessary PV modules is obtained as NPV = 36.6*1000/54=778 PV modules.

Each 16 modules will be connected in series to build 43 parallel strings. The open circuit voltage for this PV array at standard conditions is Voc = 21.7*16 = 347.2 V, while the voltage at the maximum power point of this array is 17.4*16=278.4 V. The input of PV charge controller shall sustain this level of input voltage.

The input/output ratings of the PV charge controller are determined by the output of the PV array and the battery nominal voltage. The rated power of the PV charge controller is 37 kW. In this power range it is recommended that the charge controller should have a maximum power control unit [1].

The wind turbine has a 30 kW rated power, 3ph-400V, 50 Hz output voltage, it has 2 blades, its rotor diameter is 15 m, and has a 37 m tower height. It uses a permanent magnet synchronous generator.

The wind charge controller comes after a rectifier circuit that rectifies the 3-phase variable AC voltage output from the wind turbine. The rated power of rectifier circuit is 30 kW. The rectifier circuit can be selected to have a 220 V DC rated voltage at its output. For this case a wind charge controller is selected with voltage ratings similar to the PV charge controller except that the rated power of it is 30 kW. Some companies provide a special wind charge controller to satisfy the two goals (rectify & charge control) in the same product.

The bidirectional inverter side voltages have to be matched with the battery bank voltage (220 V DC) and the 3-phase, 3*380V, 50Hz output voltage from the diesel generator. The rated power of the bidirectional inverter is selected at 30 kW rating.

Figure 4 shows a graphical representation of initial costs for different components constructing the hybrid system.

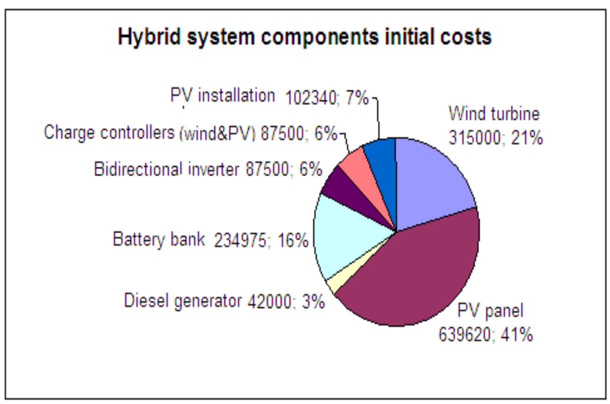

Fig. 4 Hybrid system components initial costs for Ramallah site.

II. CONCLUSIONS

Based on the simulation program results previously presented, the following conclusions can be demonstrated:

- As a result of analyzing wind, PV, diesel with a storage battery bank hybrid system to supply a load, a combination of them with wind as a main source, 50% PV contribution, 0.5 battery autonomy days, with limited operation of diesel generator (521 hour/year) forms the optimum case with a COE equals to 1.28 NIS/kWh.

- For wind-diesel hybrid system, the COE is 1.57 NIS/kWh and occurs at 0.3 battery bank AD.

- For PV-diesel hybrid system, the COE is 1.55 NIS/kWh and occurs at 90% PV contribution and AD=0.6. So using PV-diesel hybrid system is more economical than using wind-diesel hybrid system but the difference is so small. The most economical scenario is using wind-PV-diesel hybrid system as stated before.

- Using wind as a standalone system to supply load is not economical or practical choice because of low availability of wind during different times in a year (months from September to December have low average wind speeds). Higher rating is required for the wind turbine to supply a load with a certain power, also higher battery capacity (higher autonomy days) are required to supply this load. For Ramallah site a 45 kW wind turbine with AD=6 is required to supply the load that has a maximum power of 24 kW. The COE is also high; it is 3.13 NIS/kWh.

- Using PV as a standalone system to supply the load isn't also economical or practical one. Different times through a year have low solar radiation especially during winter months (December, January, and February). High capacity battery bank is required to meet the load demand (higher autonomy days). For Ramallah site a battery bank with AD=3 is required. The COE is also high; it is 3.09 NIS/kWh.

- Using diesel generator only to supply the load requires two units, each works for 12 hours daily. More fuel, so more CO_2 is produced, also more maintenance and operational costs is needed. The COE is high; it is 2.14 NIS/kWh. The amount of CO_2 produced is 86 ton/year which is too high compared with the hybrid system where the amount of CO_2 is 10.3 Ton/year.

Table 6 summarizes COE for different scenarios mentioned.

TABLE 5

COE IN (NIS) FOR DIFFERENT SCENARIOS ANALYZED

Case	Definition of the case	COE (NIS)
1	Hybrid System(Wind-PV ,Diesel with Storage battery)	1.28
2	PV only Hybrid System (PV , Diesel with Storage battery)	1.55
3	Wind only Hybrid System(Wind , Diesel with Storage battery)	1.57
4	PV stand alone (PV with Storage battery)	3.09
5	Wind stand alone (Wind with Storage battery)	3.13
6	Diesel Generator only	2.14

- High quantities of dump energy (about 54000 kWh/year) are generated due to the fact that the size of the components constituting the hybrid system are specified to meet the worst cases during the year. During the months of high level of wind speed and solar radiation, excess (dump) energy will be produced. It can be managed to use this dump energy to supply auxiliary loads such as streets lighting, water pumping, heating, and refrigeration. This will benefit the performance of the hybrid system.

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