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Optimum Design of a Stand-alone Hybrid Energy System for a Remote Village in Palestinian Territories

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Abstract— This paper proposes a method of electrification for rural areas using stand-alone hybrid system based mainly on renewable energy sources and diesel generator. The optimum size of each component in the hybrid system to electrify a small village in Palestinian territories is the main objective of this work. The small village comprises about 25 households with some service buildings. The average energy demand is 275kWh/day. The average and maximum power demand are 11.4kW and 24kW, respectively. The region has abundant solar radiation potential with a daily average 5.4kWh/m^2 and average wind speed of 4.22m/s. The optimum design for this complicated hybrid system is based on HOMER Pro software which requires incident solar radiation data, wind speed data, electrical demand profile for the village, fuel cost, equipment characteristics and costs. The optimization results showed that the best hybrid system among all feasible configurations is photovoltaic/wind/energy storage systems with diesel generator. The net present cost of the system is US$491,635 and the cost of energy (COE) produced is US$0.427/kWh. The payback period is approximately 12 years at selling price US$0.4/kWh. Sensitivity analysis are considered to study the impact of variations in average wind speed, cost of fuel, cost of storage and cost of PV modules at different maximum annual capacity shortages.

Index Terms— HOMER software; Hybrid energy systems; Stand-alone power systems; Optimization; Rural electrification

I INTRODUCTION

Palestinian Territories suffer from severe shortage of energy supply as well as the fluctuations of energy prices. The Palestinian authority has no control on borders so all energy products are bought from Israeli companies. Small fraction of electrical energy demand is locally generated in Gaza power plant and about 37 MW is imported from Jordan and Egypt [1].

The electrical energy in Palestinian territories represents about 31% of total energy consumed. The available electrical energy is insufficient to cover the needs of the local market especially the growth in electricity consumption reaches about 7%. High electrical tariff rates are imposed from the Israeli electrical company (IEC) compared with the neighboring countries.

Large number of villages and small communities still utilizing small diesel generators to cover their electrical energy demand in Palestinian territories, as most of them are isolated and far away from the electric grid. Normally the working hours of the diesel generators in those localities are limited to small periods of time. Moreover the price of diesel fuel is high and keeps increasing in addition to frequent faults which require continuous maintenance. High percentage of air pollution is released from the exhausts of the diesel generators. Therefore, the use of diesel generators is ineffective option for rural electrification.

Palestinian Energy Authority (PEA) is paying great attention to exploit the photovoltaic and wind energy to mitigate the energy crisis of the isolated villages and localities. Palestine is granted high solar radiation potential and high sunshine hours throughout the year in which the horizontal yearly average daily solar radiation is about 5.6 kWh/m^2 with about 3000 sunshine hours [3]. The wind energy potential in Palestinian territories is generally low but there is an acceptable potential in specific locations which can be utilized in small scale wind turbines [1, 4].

Neither photovoltaic nor wind energy can supply independently an uninterrupted energy due to seasonal and daily weather variations as well as the stochastic nature of wind energy. Therefore, in order to familiarize with those conditions in a stand-alone systems, photovoltaic energy conversion system (PVECS) and wind energy conversion system (WECS) are usually joined. A completely utilization of all the available energy can hardly been accomplished without an efficient energy storage system (ESS) or back-up system like conventional diesel generator (DG). This type of power system is called a hybrid power system.

Hybrid energy system is defined as a system which integrates renewable energy sources (RES) with other sources as diesel generator or storage system to meet electric power energy needs to a specific load [5] which improves the reliability of

the system as well as the size of the storage system can be reduced slightly as there is less reliance on one unique energy source [6].
In this paper, a standalone hybrid system based on PVECS/WECS with diesel generator is demonstrated and banks of lead acid battery energy system is used to supply the electrical requirements for a Palestinian small village in Hebron governorate. Figure one shows a schematic diagram of the considered standalone hybrid system and details about each component is presented in the next sections.

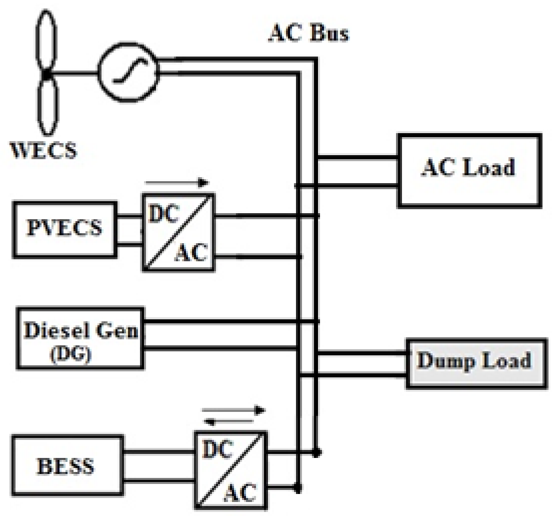

Figure 1. Schematic of the proposed standalone hybrid system

To analyze and design such a micro power system is a great challenge because of huge number of possibilities and the uncertainty in some important factors as the price of some devices, fuel, data, etc. The intermittent of the electrical energy produced from PVECS and WECS add further complexity to the analysis. HOMER pro software is utilized to overcome the challenges.

Some investigations have been done to find the optimum design of hybrid systems based on renewable energy sources (RES) are found in [7-20]. In [7] the feasibility of using hybrid systems based on WECS, PVECS and diesel generators to supply the energy needs for a household was studied using Homer software and the results showed that the most economical option was wind-hydrogen-battery hybrid system, which had a total net present cost of US$63,190 and a cost of energy of US$0.783/kWh. A similar study was implemented in [8] for isolated island but without utilizing diesel generator as aback up and the results prove the technical and economic feasibility of employing solar/wind/battery hybrid system to support electrical energy to the assigned load. Similarly, in [9] a feasibility analysis of renewable energy supply options for a grid-connected large hotel located in Australia was investigated and the analysis demonstrated that renewable energy supply is both technically feasible and economically viable.

Using the similar approach, in [10] a cost benefit and technical analysis of rural electrification alternatives in southern India was investigated and the result confirmed the feasibility and applicability of using PVECS/WECS/hydro hybrid system configuration with battery energy storage system. In [11] a focus on the optimal design, planning, sizing and operation of a hybrid system based on renewable energy sources to minimize the lifecycle cost was performed. In [12] a hybrid renewable energy system consisted of PVECS/WECS with battery energy storage system (BESS) and diesel generators for remote area in the western region of Abu Dhabi was modeled and designed using Homer software to meet three different loads and the obtained results showed that the hybrid system with 15% of photovoltaic and 30% of wind turbine penetration found to be the optimal system for 500 kW average load with initial cost of US$4,040,000 and total net present cost of US$14,504,952 over 25 years. In ref. [13] the authors performed a study to compare and analyze different off-grid configurations for electrification of countryside village based on diesel generator, hydro/diesel, and PVECS/diesel generator. In [14] the potential of using hybrid energy system configuration in rural areas based on PVECS and diesel generator was analyzed and compared with standalone diesel generator. In [15] different energy generation technologies were compared with a micro-grid supplied by a biomass gasifier power plant using HOMER software. In [16] a feasibility study using HOMER software was done to investigate the performance of grid connected based on PVECS to supply a dairy farm in north Algeria with 23.6kWh daily load. In [17] a hybrid power system based on off grid wind/PV was investigated to electrify an isolated island in China and the cost of produced energy from this system as about US$0.595/kWh. In [18-20] further researches are performed to find optimum hybrid power systems based mainly on renewable energy sources using Homer software.

II HOMER PRO SOFTWARE

The analysis and design of micro-power systems are not easy job because of having large number of design options as well as the need to study the effect of changing different parameters. The intermittent nature of renewable energies add further complexity to the analysis and design. HOMER pro software came to deal with such heavy tasks.

HOMER stands for hybrid optimization model for electric renewable and it is a micro power optimization model that simplifies the mission of finding the optimum design of both off-grid and grid-connected power systems for a various applications through performing three primary tasks: simulation, optimization, and sensitivity [21].

The simulation determines if the system is feasible or not and it is considered viable if it adequately serves the electric and thermal loads and satisfies any other constraints imposed by the user. The life-cycle cost of the system is also estimated which is the total cost of installing and operating the system over its lifetime [21]. The life-cycle cost is a proper indicator for selecting the best hybrid power system configuration.

The total net present cost (NPC) is utilized by HOMER pro to represent the life-cycle cost of the system. Total NPC is defined in eqn. (1) [21]:

$$NPV = C_{tot-ann}/CRF\ (i, T_{proj}) \quad (1)$$

Where $C_{tot-ann}$ is the total annualized cost, i is the annual real interest rate (the discount rate), T_{proj} is the project lifetime, and *CRF( )* is the capital recovery factor, given by the eqn.(2) [21]:

$$CRF(i, N) = i(1+i)^N/((1+i)^N - 1) \quad (2)$$

Where i is the annual real interest rate and N is the number of years. HOMER uses the eqn. (3) to calculate the levelized cost of energy [17]:

$$COE = C_{tot-ann}/(E_l + E_{def} + E_{g-sales}) \quad (3)$$

Where $C_{tot-ann}$ is the total annualized cost, E_l and E_{def} are the total amounts of primary and deferrable load, respectively and $E_{g-sales}$ is the amount of energy sold to the grid per year. To calculate the salvage value of each component at the end of the project lifetime, HOMER uses the eqn. (4) [21]

$$Salvage = C_{rep} * T_{rem}\ /\ T_{comp} \quad (4)$$

Where C_{rep} is the replacement cost of the component, T_{rem} is the remaining life of the component, and T_{comp} is the lifetime of the component.

HOMER simulates different configurations of the hybrid system during the optimization process in which the infeasible options are rejected and the feasible options are ranked according to total net present cost (NPC). The feasible option with the lowest total net present cost is presented as the optimal system configuration [21].

The sensitivity analysis is very important feature of HOMER software. This facility enables the user to study the effect of varying a single input to a range of values.

III Site description, load demand and hybrid system resources

a. Site description and load demand:

There are still rural Palestinian villages and communities suffer from lacking electricity services and most of them are located in Hebron governorate. A small village from Hebron governorate was taken as a case study at coordinates 31.5326° N, 35.0998° E. The village is far away from electric network and the main job of its inhabitants is farming and cattle breeding. The village includes about 25 household in addition to elementary school, clink and small mosque.
The standard of living in this village is reasonable so each household included the basic electrical equipment. The electrical equipment of a typical residential building included TV, refrigerator, one movable fan, washing machine, lighting equipment, personal computer, electric heater in addition to small appliances. This information was based on a survey performed in the village and its surroundings and consequence with other load profiles proposed by other local and international researchers [8, 7, 22].

The village average energy demand is shown in Figure 2 which is considered the primary load that should be fed by the system otherwise it is classified by the software as unmet load. Each season has the corresponding load profile. The load profiles were derived based on a survey performed in the village. The average energy demand is 275kWh/day. The average, high daily and minimum daily power demand is observed to be 11.4kW, 24kW and 4.5kW, respectively .The average load factor is 0.284.

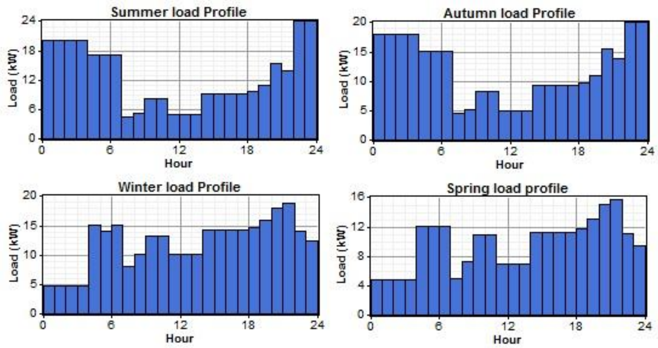

Figure 2. Load profile of the village for all seasons (primary load)

The hybrid system resource refers to anything coming from outside the system that is used by the system to generate electric or thermal power which includes in this study solar radiation, wind speed the diesel fuel used by the diesel generator.

b. Solar radiations profile

Palestinian territories has sufficient solar radiation potential to utilize solar electricity specially the photovoltaic energy since the daily average of solar radiation on horizontal surface was measured to be 5.45 kW h/m^2 day [23-24]. Figure 3 shows the monthly average daily solar radiation input data of the selected site [23] to HOMER software, which in role generates synthetic 8760-hour total solar radiation data set utilizing special procedure established by Graham and Hollands [25].

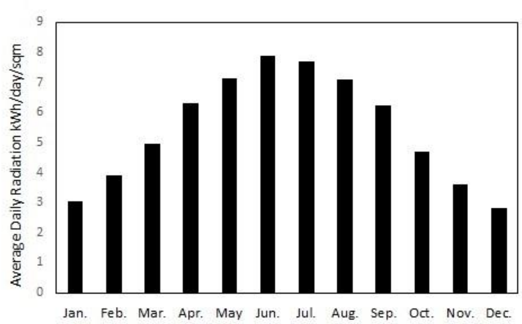

Figure 3. Average daily solar radiation of the village (case study)

c. Wind speed profile

The potential of wind energy in Palestinian territories is generally limited [1, 4] but in some locations the average wind speed may reach 4-5m/s which is sufficient for small scale wind turbines. Figure 4 shows the climatology of wind speed for the village in Hebron governorate based on period 2000–2011 [26] and the average wind speed was calculated to be 4.22m/s.

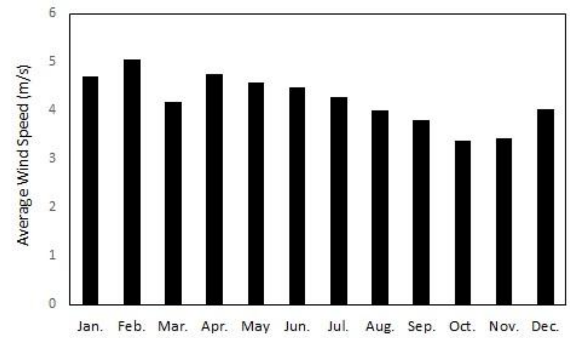

Figure 4. Average wind speed of the village (case study)

d. Diesel fuel

The user can enter or moderate the physical properties of the fuel used which is for diesel fuel: density 820 kg/m^3, lower heating value 43.2 MJ/kg, carbon content 88% and sulfur content 0.33%. The average price of the diesel fuel in Palestinian territories of this year (2016) is about 1.3 US$/L.

IV Configuration of Hybrid Energy System

The proposed configuration of the hybrid system used in this study is shown in Figure 1 and it consisted of PVECS, WECS, diesel generator (DG) and battery energy storage system (BESS). The analysis of such a complicated system is based on HOMER pro software. The HOMER pro schematic diagram of the hybrid system is shown in Figure 5.

The technical specification and cost of each component used in the software is illustrated in details. It is good practice to note that the following specifications and type of each component were the optimum scenarios and they were selected after too many simulations. The price of each component based on the local prices in Palestinian territories on 2016. The lifetime of the project is 20 years and it is assumed that the local community offers the land where the project established.

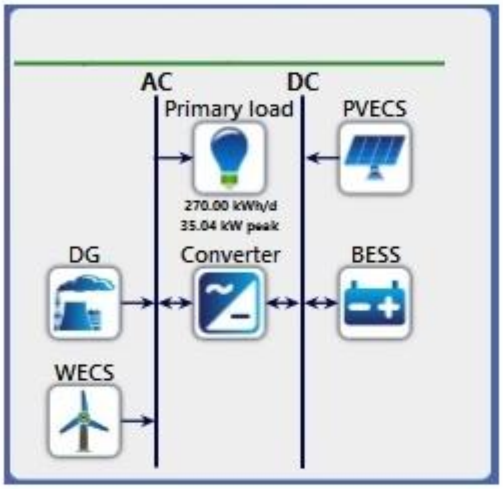

Figure 5. Homer pro schematic diagram of the proposed hybrid system

a. Photovoltaic energy conversion systems (PVECS)

The main data required by the software regarding the PVECS includes: The range of the sizes of photovoltaic modules considered in the study is wide in order to have the optimum option. The capital, replacement and O&M costs are US$2000/kW, US$1750/kW and US$20/year, respectively. The lifetime of the PVECS is 20 years. The derating factor is 80% and the system is fixed without tracking at a slope of 30° angle and 0° azimuth angle.

b. Wind energy conversion system (WECS)

Selecting the suitable WECS of a site is not an easy task as it is essential that the characteristics of the turbine and the wind regime at which it works should be properly matched. The capacity factor of the system can be a useful indication for the effective matching of wind turbine and regime [27].
The rated power of the selected wind turbine is 2.5 kW, 3-bladed upwind turbine, 5m diameter, variable speed asynchronous generator with IGBT converter. The wind turbine power profile is shown in Figure 6.

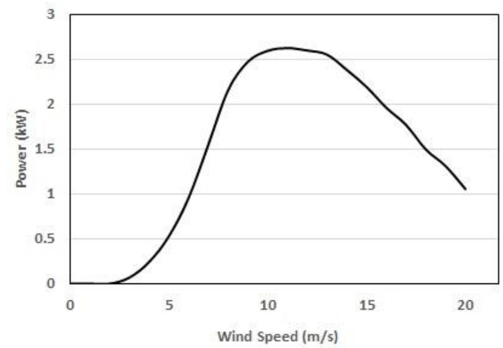

Figure 6. Wind turbine power profile

The number of wind turbines considered in the study are wide in order to obtain optimum option. The capital, replacement and O&M costs are US$8000, US$6000 and US$50/year, respectively. The lifetime is 15 years.

c. Power converter:

The converter can work as an inverter once converts electric power from DC to AC and the efficiency is assumed 90% and at the same time it can work as a rectifier once converts the electric power from AC to DC and the efficiency is assumed 85%. The sizes of power converters considered in the study are wide. The capital, replacement and O&M costs are US$1000/kW, US$1000/kW and 4US$/year, respectively. The lifetime is 15 years.

d. Diesel generator (DG):

Diesel generator is used as dispatchable energy at this study to compensate power in the lack of renewable source. The sizes of diesel generators considered in the study are wide. The capital, replacement and O&M costs are US$800/kW, US$750/kW and US$0.02/h, respectively. The lifetime of the diesel generator is 15000 operating hours.

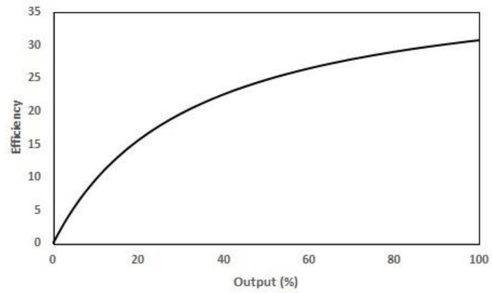

Figure 7. Diesel generator efficiency curve

e. Battery energy storage system (BESS)

The energy storage system is very important in standalone system as renewable energy sources are intermittent and stochastic in nature. The physical properties of the battery bank used in the study are: the nominal voltage 4V, nominal capacity 1900 Ah (7.6kWh), round-trip efficiency 80%, and minimum state of charge 40%. The capacity curve in Figure 8 shows the discharge capacity of the battery in ampere-hours versus the discharge current in amperes.

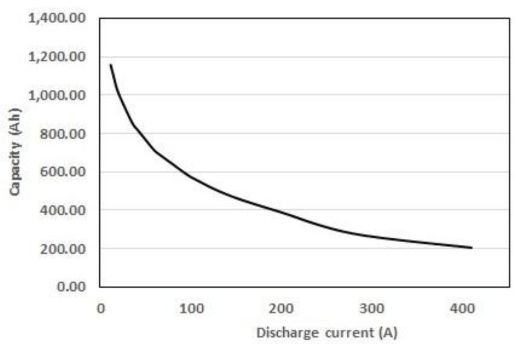

Figure 8. The capacity curve of the battery

The sizes of BESS considered in the study are wide enough to obtain optimum option. The capital, replacement and O&M costs of each battery are US$1150, US$1100 and US$10/year, respectively. The lifetime of each unit is 15000 operating hours.

V Simulation Results and Discussion

HOMER pro software shows optimization results by revealing only the least-cost configuration within each system category which means that the software suggests different type of schemes with different energy systems. After performing great number of simulations the most feasible configurations are shown below:

Configuration 1: PVECS/WECS/BESS with DG

The optimization analysis shows that the hybrid system consisted of PVECS/WECS/BESS with DG shown schematically in Figure 9 is the most economic hybrid system. It includes PVECS with 50kW, 10 WECSs, diesel generator with 18kW, 96 batteries and 38 kW converter capacity.

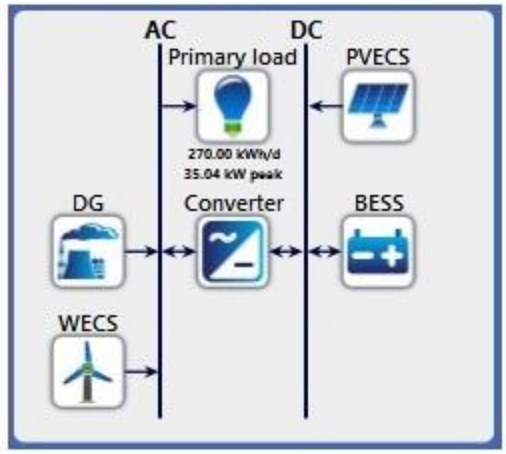

Figure 9. Schematic diagram of PVECS/WECS/BESS with DG configuration

The total capital cost of the optimum hybrid system includes the capital cost, replacement cost, O&M cost and salvage cost is about US$ 491,165 which is the net present cost of the system. The cost of energy (COE) produced by this configuration is US$0.427/kWh. The renewable energy fraction 0.93.

The monthly average electric production of the hybrid system components is illustrated in Figure 10.

The annual AC primary load is 100.35MWh and the annual excess electricity production is about 20% from the total annual energy produced. The amount of excess energy can be reduced by increasing the energy storage capacity but it is not economically wise so further analysis should be performed to deal with this energy such as utilizing it in heating water in winter, water pumping, cooling in summer, etc.

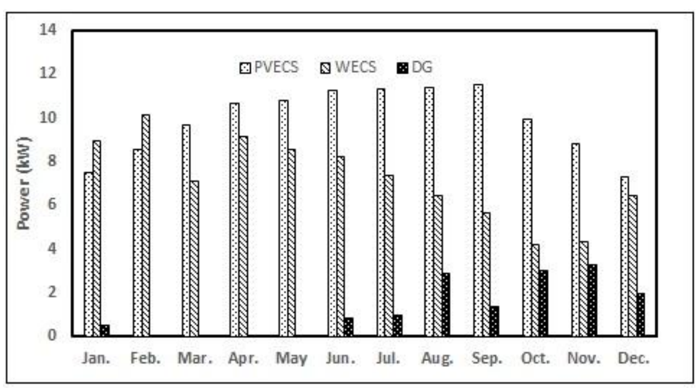

Figure 10: The monthly average electric production of the hybrid system.

The total energy production annually from PVECS is 86.8 MWh, which is about 54% from the total annual energy produced, and 86.5% from the AC primary load (PV penetration). The number of operational hours is 4391 and the capacity factor is 19.8%. The mean output per day is 238kWh/day and the levelized cost of energy from PVECS system is US$0.106/kWh.

The total energy production annually from WECS is 63MWh, which is about 39% from the total annual energy. The number of operational hours is 7638 and the capacity factor is 28.8%. The levelized cost of energy from PV system is US$0.136/kWh

The total energy production annually from diesel generator is 10.8MWh, which is about 7% from the total annual energy produced. The annual operational hours is 869 and the capacity factor is about 6.88%. The fixed generation cost is US$2.95/h; the specific diesel consumption is 0.365L/kWh while the annual diesel consumption is 3965L.

The NPC categorized by hybrid system component is shown in Figure 11, which shows that the BESS has the highest NPC while the converter has the lowest.

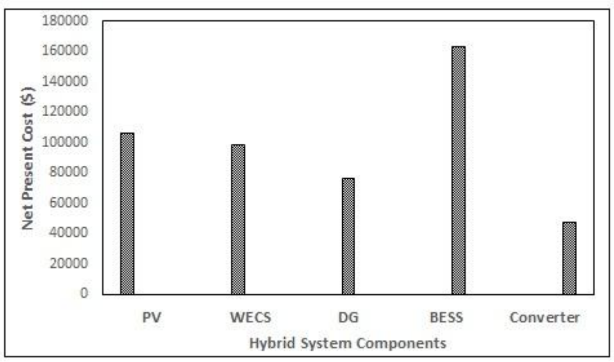

Figure 11: The net present value categorizing by hybrid system components

Figure 12 reviews the annualized cash flow for each component of the hybrid system. The maximum cost after the initial investment cost is seen to be the replacement cost for all system components. The salvage cost is low and is the highest for the battery. The diesel generator encountered high running fuel cost.

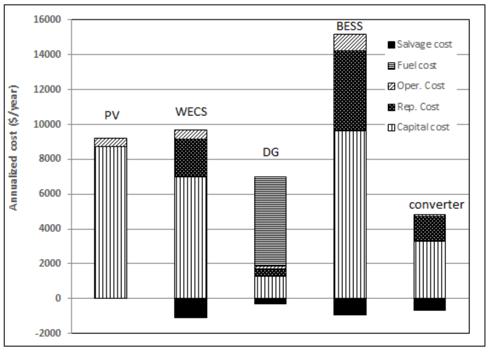

Figure 12: The annualized costs of each component of the hybrid system

For supplementary analysis on the selected optimal hybrid systems the impact of some important parameters and input data are examined. The effect of variation in average wind speed is investigated as this input variable is very location sensitive. The argument around the accuracy of the wind data can be diminished as the analysis includes a range of average wind speeds.

The effect of variation in the cost of diesel fuel is also investigated specially this parameter is very sensitive to political situation as well as depends on the country. The effect of maximum annual capacity shortage (MACS) is also investigated. This is very important, as sometimes there is a possibility to unmet some part of the load at specific time, which consequently may affect the result of optimization result.

The solar radiation is not subjected to sensitivity analysis, as the annual average solar radiation data are mostly similar for many years according to historical data.

Figure 13 and Figure 14 shows the impact of the variation on the average wind speed and the cost of diesel fuel at 0% and at 10% maximum annual capacity shortage (MACS), respectively.

Figure 13 shows that the lowest COE is US$0.401/kWh at average wind speed 4.6m/s and fuel price of US$1.1/L. It is clear that the wind speed is affecting the COE. Having high cost of diesel fuel can be lessened by higher wind speed.

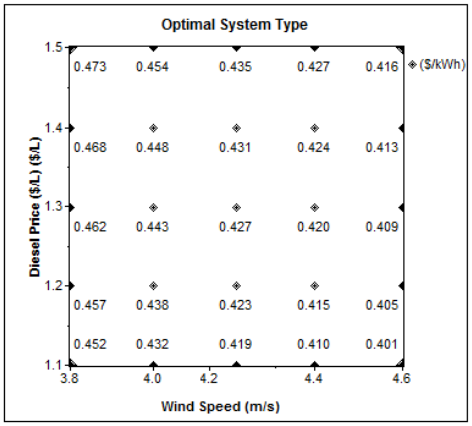

Figure 13. Impacts of variations of average wind speed and cost of fuel on the COE (US$/kWh) at 0% MACS in the configuration Wind/PV/DG with BESS

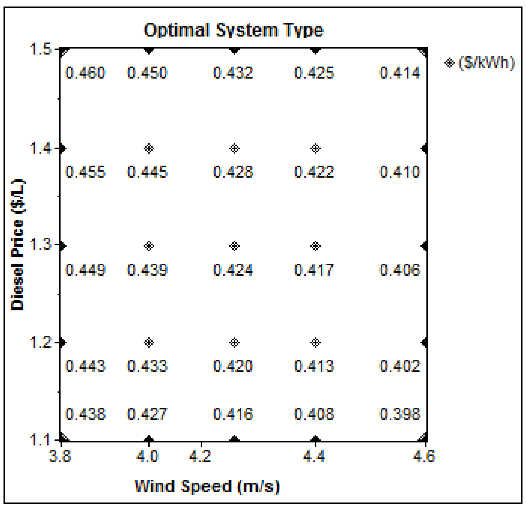

Figure 14: Impacts of variations of average wind speed and cost of fuel on the COE (US$/kWh) at 10% MACS in the configuration Wind/PV/DG with BESS

Figure 14 shows that the lowest levelized COE is US$0.398/kWh at average wind speed 4.6m/s and fuel price of US$1.1/L.

From Figures 13 and 14 the least levelized COE is obtained at about 4.6m/s average wind speed and at US$1.1/L fuel cost, which means that the average wind speed, is one of the prevailing factors that determine the COE as well as the optimum hybrid system. The wind energy can be extracted even the average wind speed reduces to 3.8m/s.

Allowing a maximum annual capacity shortage (MACS) up to 10% caused 0.2% unmet electric load which is about 161kWh/year. This has no remarkable effect on the COE.

The sensitive analysis shows that the cost of PV modules affects the COE remarkably. If the cost reduces to 70%, the COE reduces to about 6% while 30% increase in the cost increases the COE to about 6% as well. In same context, if the cost of BESS reduces to 70% the COE reduces to about 9%, which implies that, the cost BESS has greater effect on the COE than the cost of the PV modules.

Configuration 2: PVECS/BESS with DG

The optimization analysis shows that the hybrid system consisted of PVECS/DG with BESS is one of the feasible hybrid system option among number of different configurations. It includes PVECS with 84kW, diesel generator with 16kW, 144 batteries and 40kW converter capacity. The COE produced by this configuration is US$0.479/kWh with 0.93 renewable energy fraction.

The annual AC primary load is 100.355MWh. The PVECS contribution is 93% while the diesel generator contribution is 7% from the total annual energy produced.

The amount of air pollution produced in configurations 2 is greater than that of configurations 1 as shown in Table 1 and this is because the renewable energy fraction in configuration 1 is higher.

TABLE 1:
Environmental impacts of the feasible hybrid system options

	Configuration 1	Configuration 2
Pollutant	Kg/year	
Carbon dioxide	10442	16168
Carbon monoxide	25.8	39.9
Unburned hydrocarbons	2.85	4.42
Particulate matter	1.94	3.01
Sulfur dioxide	21	32.5
Nitrogen oxides	230	356

To find out the main parameters that affect the COE from this configuration, different sensitive analysis are implemented. The effect of MACS on the cost of produced energy is trivial, as the cost of produced energy at 0% MACS is US$0.479/kWh while it is US$0.477/kWh at 5 and 10% MACS.

Increasing the price of BESS to 20% increases the cost of energy to about 3.7% while reducing the price to 20% reduces the cost of energy to about 6%. This implies that the effect is limited. Increasing/reducing the price of PV arrays to 20% increases/reduces the cost of energy to about 6%. The price of diesel generator has trivial effects on the cost of produced energy as it covers only 7% of the load.

Configuration 3: PVECS with BESS

In fact, this configuration is not feasible with respect to configurations 1 and 2 but it is good practice to further analyze it as it is simple and easy to install. To supply the load using this configuration a PVECS modules with 102kW, 288 batteries and 36kW power converter are required. The COE produced by this configuration is US$0.651/kWh with 100% renewable energy fraction. The amount of air pollution produced in this configurations zero.

The sensitivity analysis shows that reducing the price of PV modules and BESS by 20% will reduce the COE to about US$0.523/kWh, which is still high, greater than configurations 1, and 2.

To estimate the payback period of the project, different selling prices of kWh to the consumers will be considered. The Payback period means number of years required to recover the cost of the investment. Table 2 shows the payback period of the project for different configurations using different selling prices.

TABLE 2:
Payback period of the project

	NPC (USD)	Energy sold kWh	COE USD/kWh	Payback Period (yrs)
Config. 1	491165	100350	0.45	10.87
			0.4	12.2
Config. 2	550841	100350	0.45	12.9
			0.4	13.72
Config. 3	571200	100350	0.45	12.64
			0.4	14.23

It is good practice to note that surplus energy is produced in each configuration, which can be utilized for different applications, which in role increases the profits and consequently reduces the payback period.

The profits earned from reducing gas emissions are not considered in this research as no such motivation is available in Palestinian territories.

VI Conclusion

The stand-alone hybrid energy system is one of the strong alternatives to electrify rural communities far away from electrical grid provided that future prices trend of renewable energy technologies are decreasing.

The PVECS/WECS/BESS with diesel generator is the most economic hybrid system and capable of supplying electricity at a cost of US$0.427/kWh. The total net present cost (NPC) of the system is US$491,365 requiring an initial capital investment of US$342,800. The capacity of PVECS is 50kW, 10 WECS of 2.5kW rated power each, 96 batteries of 1900Ah each and 18kW diesel. The system can provide total energy demand of the village (275kWh/day) without any interruption to power supply. The contribution of diesel generators is low which is one of the main objectives of this work. The payback period is 12.2 years at selling price US$0.4/kWh.

The hybrid system consisted of PVECS/BESS with DG is the second most economic hybrid system with levelized COE US$0.479/kWh. The payback period is 13.7 years at selling price US$0.4/kWh.

The configuration consisted of PV modules and BESS is investigated with sensitive analysis and the results shows that the configuration is not feasible with respect to other configuration. The payback period is 14.2 years at selling price US$0.4/kWh.

The sensitivity analysis showed that the average wind speed is one of the predominant factors in determining the optimum hybrid system and the COE. The effect of the variations on the cost of PV module, BESS and diesel generator is investigated. The effect of maximum annual capacity shortage (MACS) on the excess electricity fraction is generally trivial.

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