ISSN 2278-3091
Volume 9, No.5, September - October 2020
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse274952020.pdf
https://doi.org/10.30534/ijatcse/2020/274952020

HOMER-Based Optimal Design of Hybrid Power Systems for Educational Institution

A. H. Abu Yahya [1], A. A. Shawish[2], M. B. Al-Jilani [3], E. A. Feilat [4]
[1]The University of Jordan, Jordan, Ahmad1997abuyahya@outlook.com
[2] The University of Jordan, Jordan, Ammar.a.shawish@gmail.com
[3] The University of Jordan, Jordan, Mohammad.aljilani1997@gmail.com
[4] The University of Jordan, Jordan, e.feilat@ju.edu.jo

ABSTRACT

This paper presents the concept of optimal design of hybrid power systems as alternative power generation source for educational institution. In this work, three different configurations of hybrid power generation systems are proposed. These hybrid systems include, namely, PV-Diesel-Battery, PV-Grid, and PV-Wind-Diesel-Battery hybrid systems. The proposed systems are optimally designed using the Hybrid Optimization Model for Electric Renewable (HOMER) software. The best hybrid system design is chosen based on economic comparisons, environmental effects, and social acceptance to supply the load demand. The economic comparisons among the different proposed hybrid systems are used to select the hybrid system which has the lowest net present cost (NPC) and cost of energy (COE) values and the highest internal rate of return (IRR). Moreover, a comparison of environmental impacts between the proposed hybrid systems based on the percentage reduction in carbon emission is performed. Furthermore, the paper considered the social impact of installing a hybrid power system is considered.

Key words: Microgrid, optimization; HOMER, renewable energy; cost of energy; net present cost.

1. INTRODUCTION

Energy is considered one of the human being characteristics because of the need for energy in all aspects such as lightning, industry, transportation, telecommunication, and heating. So, energy attracts the attention of countries as a fundamental need that the governments must provide to their citizens. Nowadays, energy becomes a big field for engineers, researchers, and companies to compete in making it more efficient and to find new methods for generating energy which lead to social welfare. Energy is a crucial issue for the economic growth and social development of any country.

The electricity market is getting bigger every day, in some countries, companies sell and buy electricity in the stock markets, so its prices are changing according to bids and offers in the market. Also, electricity prices vary according to the used technology [1].The educational institution is located in Amman city (32º0.9' N, 35º52.3' E) has relatively high amount of electric energy consumption, especially during midday hours. Consequently, a high yearly electricity bill as the load is supplied from the national grid which leads to high COE. Therefore, an optimal alternative for this issue is the integration of clean energy sources such as solar and wind energy sources.

HOMER computer modeling software is a global standard for optimizing microgrid design in all sectors, from village power and island utilities to grid-connected campuses and military bases. Originally developed at the National Renewable Energy Laboratory and enhanced and distributed by HOMER Energy [2].

The following sections present case studies that focus on selecting the best hybrid generation system for a specific site. A comparison between three different hybrid systems has been simulated and optimized for feeding a rural village [3]. A techno-economical study of a PC-Diesel power system based on renewable energy available locally for a remote island has been done [4]. Three different configurations have been compared for supplying electricity to a modeled load comprising a grid alone, grid and solar PV, and DEG, battery banks, and solar PV system [5]. Three scenarios of off-grid systems have been investigated and compared to provide sustainable energy for a small village [6]. Based on economic analysis, four different hybrid configurations were considered to power for a rural area [7]. A feasibility study of a hybrid renewable energy system considering a combined system of solar-wind-diesel has been performed for rural and remote areas [8]. A comparative study of economic viability between different off-grid power generation systems for an industrial plant is carried out using HOMER software [9].

This paper aims to introduce a consistent design approach for a hybrid power generation system for supplying a peak load of 9.8 MW. The selection of the best hybrid power system is accomplished by making economic comparisons among different hybrid power generation configurations. Also, this study presents the percentage reduction in carbon emissions by each proposed hybrid system based on supplying the load by auxiliary stand-alone diesel-engine generators (DEGs) selected as a benchmark.

The paper is organized as follows. Section II presents the available energy resources and load profiles for the considered location. Section III discusses the system design of different hybrid system configurations. Selection of the optimal hybrid system based on the simulation results is demonstrated in Section IV. Section V presents the selection of the proposed optimal hybrid system that will serve the load. Lastly, conclusion is presented in section VI.

2. ENERGY AND LOAD PROFILES OF THE INSTITUTION

Solar and wind data of the load were collected using NASA Surface Meteorology and Solar Energy (SSE) database[10]. The database gave the monthly average wind speed values at 50 meters above the earth's surface for over 10 years (July 1983-June 1993).The annual average wind speed at the load site is 5.43 m/s. A monthly wind speed profile is shown in Figure1.

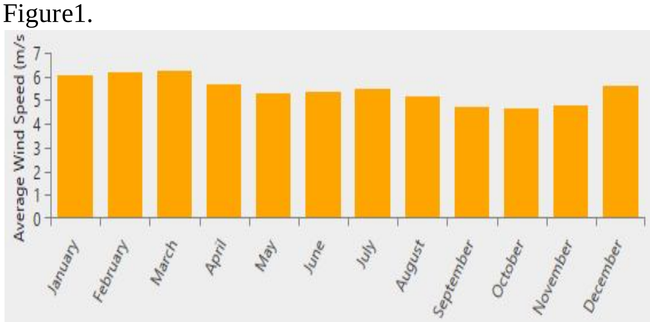

Figure 1: Monthly Average Wind Speed

Solar data is also obtained by HOMER from NASA surface meteorology database corresponding to the latitude and longitude. Using the coordinates, the monthly solar radiation and clearness index are shown in Figure 2. The annual average solar radiation is 5.19 kWh/m²/day.

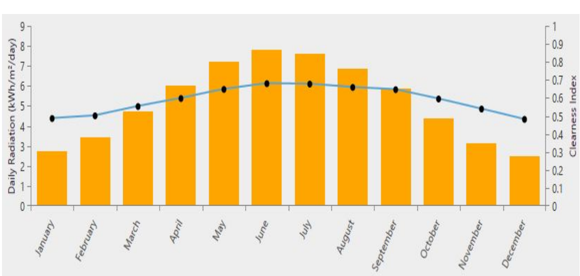

Figure 2: Monthly Average Solar Radiation And Clearness

The load profile consumption has been studied and suitably modeled to emulate the exact load profile of the considered site.In the HOMER model, the primary load is the electrical demand that the power system must meet at a specific time. Hourly data has been uploaded into the HOMER model [11]. The average daily demand is 1.8 MW while peak demand is 5.2 MW. Figure 3 shows the dailyload profile which represents the amount of power consumption forsingle day hours. Daily energy consumption is concentrated around midday hours through which all facilities are working and consuming energy.

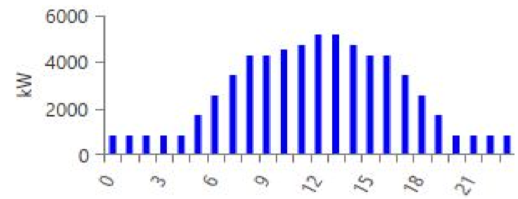

Figure 3: Daily Profile of Load Data

A seasonal profile that presents minima, maxima, and average power consumption for a single month is depicted in Figure 4.

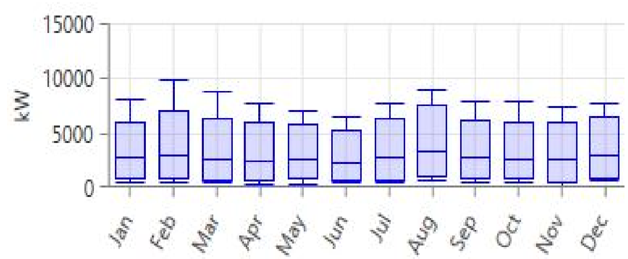

Figure 4: Seasonal Profile of Load Data

Yearly profile data map (DMap) that represents the kW power consumption for each hour during the 365 days of a year is shown in Figure 5. Examining Figure 5, one can observe that the load consumption starts from around 7 AM when facilities start consuming energy and continue almost to 6 PM at the end of the day with peak load at midday hours.

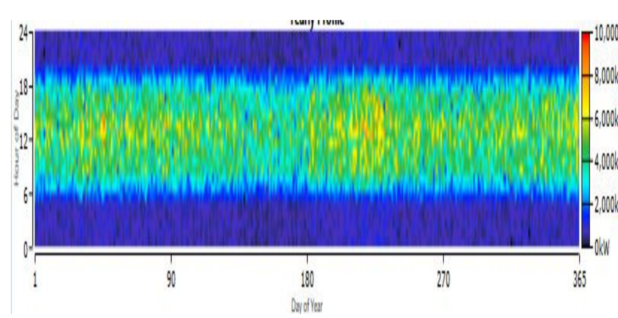

Figure 5: Yearly Profile of Load Data

3. PROPOSED DESIGNS OF HYBRID POWER GENERAION SYSTMEMS

The HOMER software calculates the operating cost and maintains energy balance for each hour of a year according to the algorithm shown in Figure 6 [2].

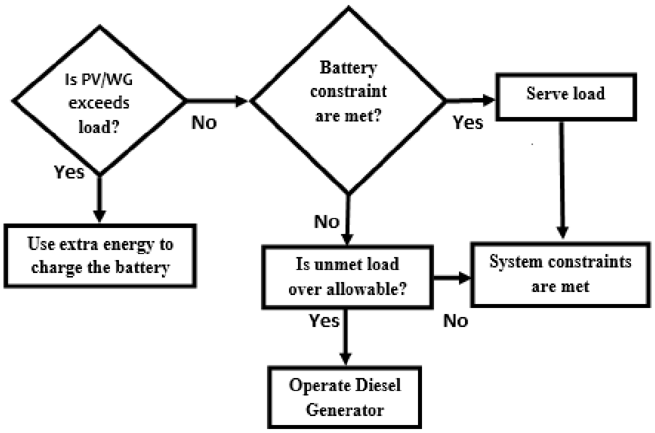

Figure 6: HOMER Simulation Algorithm

Three hybrid power generation systems, namely, PV-Diesel-Battery, PV-Grid, and PV-Wind-Diesel-Battery hybrid systems have been designed and optimized using HOMER software. The simulation outcome comprises different renewable energy sources such as Photovoltaic (PV) modules, Wind turbines, and DEGs.

3.1 Design I: PV-DG-Battery Hybrid Power System

For the case of the first design (Design I), shown in Figure 7, the four DEGS are connected to the AC bus bar, the battery units and PV panels are connected to the DC bus bar, while the (back-to-back) converter connected between AC and DC bus bars. The primary load has a maximum load of about 6.5 MWh/day, and a peak load of about 9.8 MW.

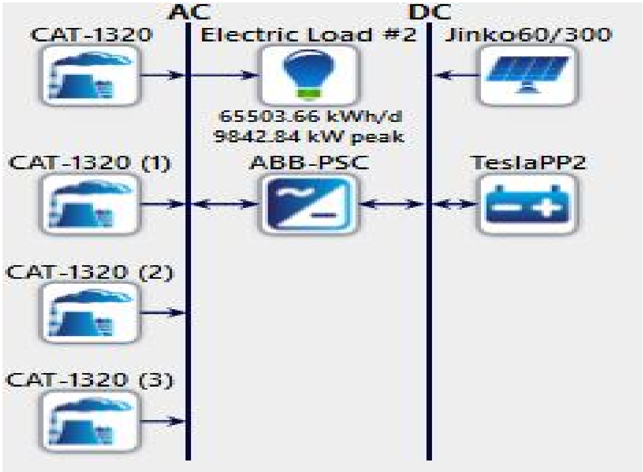

Figure 7: Schematic Diagram of PV-Battery-Diesel Hybrid System

3.2 Design II: PV-Grid Hybrid Power System

The second design (Design II), shown in Figure 8, has a Grid-based generation with PV panels for the same amount of load.

3.3 Design III: PV-Wind-DG-Battery Hybrid System

The third design (Design III) has wind turbines besides to the PV modules, three DEGs, battery units, and converter for the same amount of load as shown in Figure 9. In this work, PV modules ofJinko Eagle PERC60 300W, wind turbine of Generic 1.5 MW, battery unitsof Tesla Powerpack 210 kWh, DEGof CAT-1320kVA-50Hz-CP, and converter ofABB PSTORE-PCS have been used.

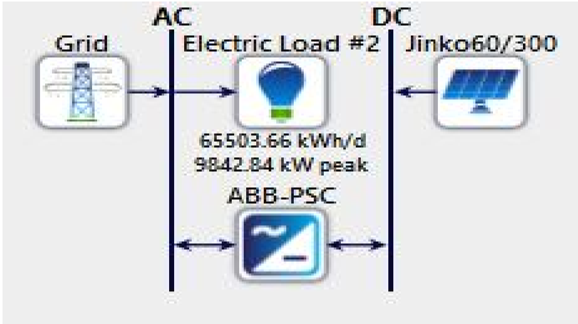

Figure 8: Schematic Diagram of PV-Grid Hybrid System

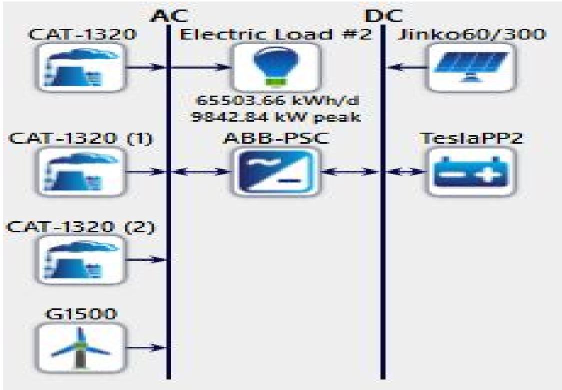

Figure 9: Schematic Diagram of PV-Wind-Diesel-Battery Hybrid System

4. SIMULATION RESULTS

The simulation results are provided in terms of optimal systems by the HOMER software. The optimization results are presented categorically for a sensitive parameter. The results are sorted in order of increasing the NPC or COE. The optimal hybrid system is the system which has the lowest NPC in the optimization table. For each proposed hybrid system, there are economic and environmental results used in this work to select the best hybrid power system for the load. Simulation and optimization results provide lots of details for the proposed hybrid systems such as component sizes, economic, and emission results.

4.1 Components Size and Cost

The size of components for each hybrid system design is selected by using optimization and simulation algorithms provided by HOMER. Sizes of components of the three designs are given in Table 1.

According to the local market, the cost summary of all components in the three designs is shown in Table 2.

Table 1: Sizes of Components

Component	Design I	Design II	Design III
PV modules (MWp)	16	16	13.351
Wind turbine (MW)	-	-	1.5
Battery (# of units)	89	-	105
DEG (# of units)	3	-	3
Converter (MW)	12.240	13.227	7.235

Table 2: Cost Summary of Components

Parameter	Design I	Design II	Design III
NPC (million USD)	21.7	10.5	24.5
COE (USD/kWh)	0.1	0.0331	0.113
IRR (%)	25	80.9	45.8
Discount payback period (yr)	5.35	1.4	2.59
Capital (initial) cost (M USD)	11.8	12.3	15.5

4.2 Economic Results

In this study many economic parameters for each design such asNPC, COE, internal rate of return (IRR), Discount payback period, and Capital cost are calculated. NPC is the present value of all the costs of installing and operating that component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime [11].

The COE is the average cost per kWh of useful electrical energy produced by the system. The NPC and COE parameters are used to select and indicate the best hybrid power system from an economic perspective. The economic results like NPC in million USD, COE in USD/kWh for each hybrid system design, percentage IRR, the discount payback period in years, and Capital cost in million USD are presented in Table 3 below.

Table 3: Economic Results

Item	Capacity	Capital cost (USD)	Replacement (USD)	O&M (USD)	Life time (Yr)
PV module	1 kw	704.00	704.00	0.50	25.00
Battery Unit	210 kWh	801.85	801.85	0.5	7
Inverter	1 (kw)	80	80	0	20
DEG	1056 kw	140,000	140,000	0.15	35
Wind Turbine	1500 kw	3000000	3000000	30000	20

The cash flow is crucial in visualizing revenues and expenses. The cash flow can be divided yearly or monthly or into any period you want. Figures 10-12 show the cash flow incomes and outcomes of three designs distributed over the lifetime of the project. Each bar represents either a total inflow or a total outflow of cash for a single year.

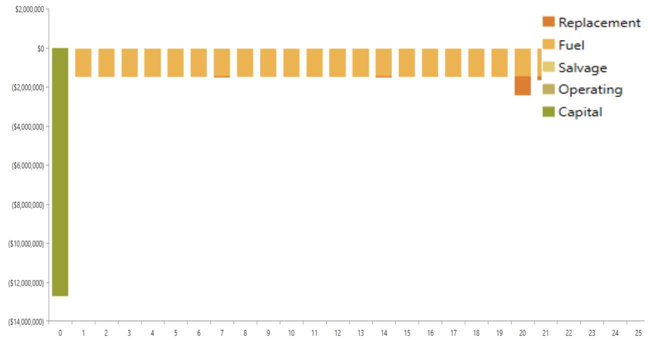

Figure 10: The Cash Flow of the PV-Battery-Diesel Hybrid System

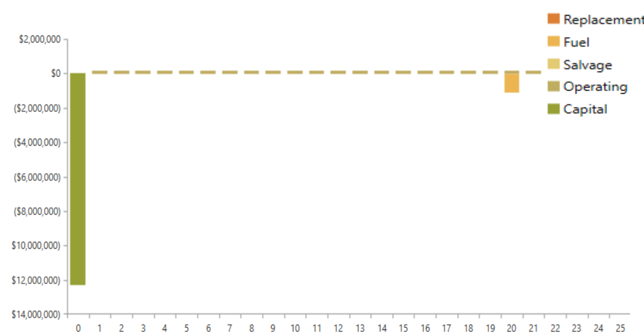

Figure 11: The Cash Flow of the PV-Grid Hybrid System

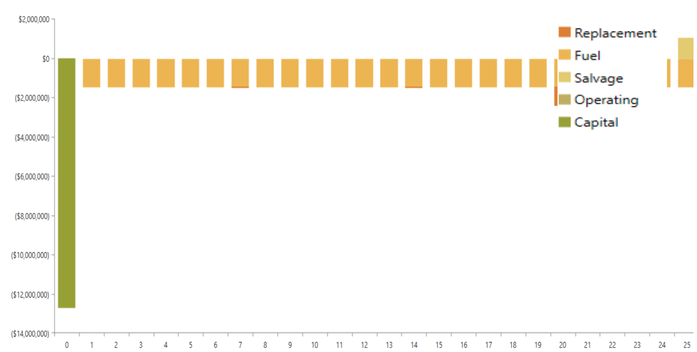

Figure 12: The Cash Flow of the PV-Battery-Diesel Hybrid System

4.3 Power Production Results

The annual production of each component of three designs is shown in Table 4.

Table 4: Economic Results

Parameter	Design I	Design II	Design III
PV modules (kWh/yr)	27,266,307	27,266,307	22,752,053
Battery Units (kWh/yr)	4,827,664	-	5,173,895
DEGs (kWh/yr)	6,420,668	-	4,807,277
Wind Turbine (kWh/yr)	-	-	2,806,090

The corresponding annual power production for renewable energy components (PV modules, Wind turbines) and the state of charge of batteries are visualized as follow:

4.3.1 Design Ⅰ: PV-DG-Battery Hybrid Power System

In HOMER software, a Data map (DMap) figure represents the power produced during a day hours for 365 days in a year using colors. For each power value, there is a certain color degree to indicate the amount of power produced at a certain hour of a certain day. The total amount of power produced by the PV modules over a year is shown as DMap in Figure 13. The total annual power produced by the PV modules is around 27,266,307 kWh/yr.

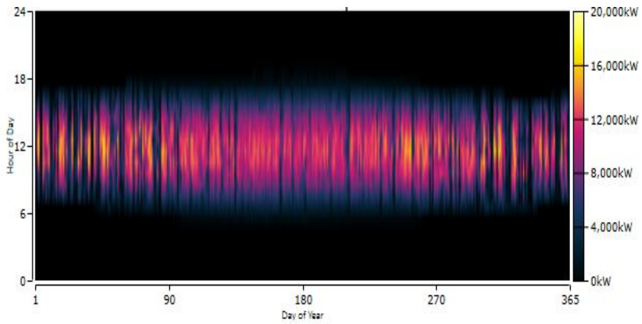

Figure 13: Annual PV Output Variation (DMap) of Design I

Through day hours, PV modules supply the demand and the excess power goes to charge the battery units. On the other hand, through night hours the load is met by only DEGs and the battery units. State of Charge data map DMap represents the state of charge for storage system during a day hours for 365 days in a year using colors.

For each power value there is a certain color degree to indicate the state of charge at a certain hour of a certain day as shown in Figure 14. From the figure below the state of batteries is almost between (25-90) %. The darker red color means the state of charge goes to maximum. The annual throughput is 4,827,664 kWh/yr.

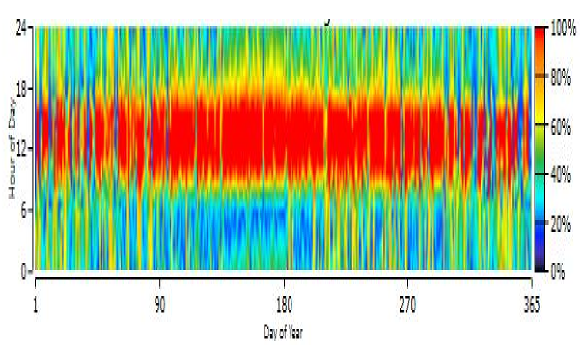

Figure 14: State of Charge of Battery Units DMap of Design I

4.3.2 Design II: PV-Grid Hybrid Power System

For the second design, the total amount of power produced by the PV modules over a year is shown as DMap in Figure 15. The annual power produced by the PV modules is around 27,266,307 kWh/yr.

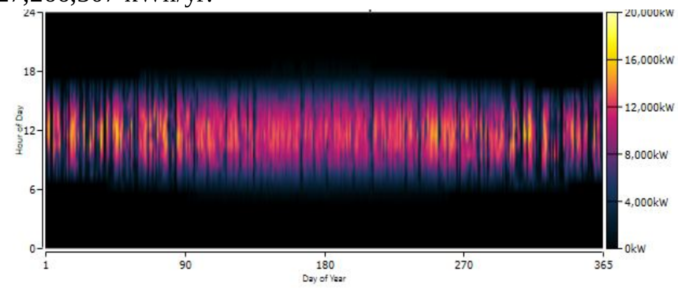

Figure 15: Annual PV Output Variation (DMap) of Design II

The annual energy purchased from the grid variation data map (DMap) represents the energy purchased during a day hour for 365 days in a year using colors as shown in Figure 16. From Figure 16 the load purchased energy at night hours where the PV modules do not produce energy. The total annual amount of energy purchased from the electrical power grid is around 8,895,309kWh.

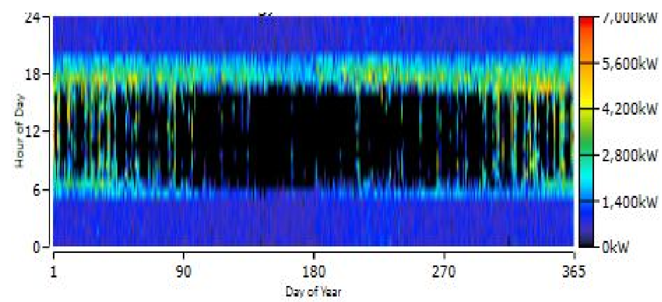

Figure 16: Energy Purchased From the Grid

On the other hand, The annual energy sold to the grid variation data map (DMap) represents the energy sold during day hours for 365 days in a year using colors as shown in Figure 17. From the figure below excess energy from PV modules at day's hours is sold back to the grid. The total annual amount of energy sold to the electrical power grid is around 11,090,520kWh.

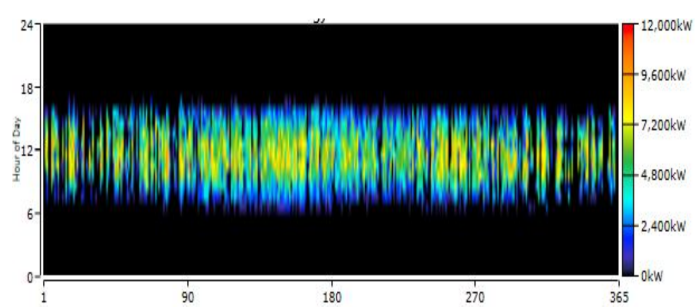

Figure 17: Energy Sold to the Grid

4.3.3 Design II: PV-Wind-DG-Battery Hybrid System

For the third design, the total amount of power produced by the PV modules over a year is shown as DMap in Figure18. The total annual power produced is around 22,752,053 kWh/yr.

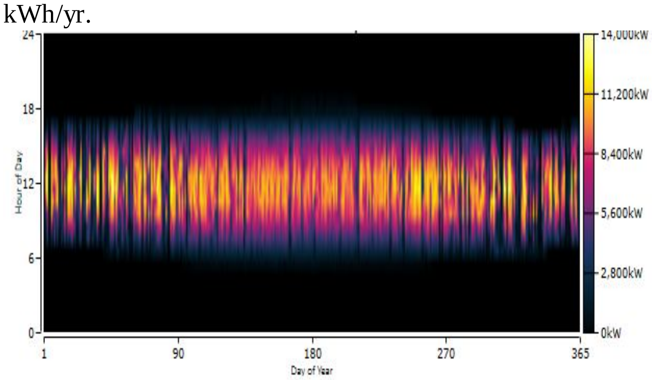

Figure 18: Annual PV Output Variation (DMap) of Design III

The Annual wind turbines output variation DMap represents the power produced during a day hours for 365 days in a year using colors. For each power value there is a certain color degree to indicate the amount of power produced at a certain hour of a certain day as shown in Figure 19. The total annual power produced by the wind turbines is around 2,806,090 kWh/yr.

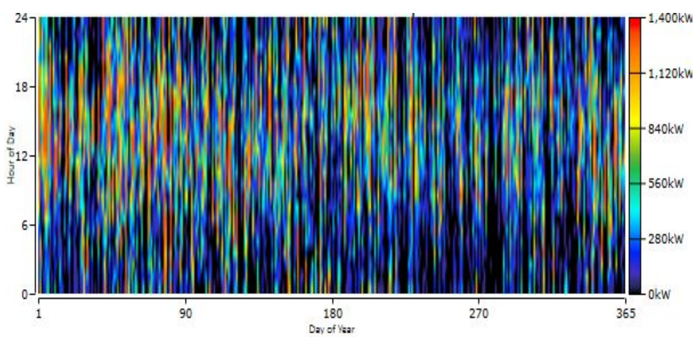

Figure 19: Annual Wind Turbine Output Variation (DMap)

The state of charge data map DMap of the third design is shown as a DMap in Figure 20. From the figure below the state of batteries is almost between (25-90) %. The darker red color means the state of charge goes to maximum. The annual throughput is 5,173,895 kWh/yr.

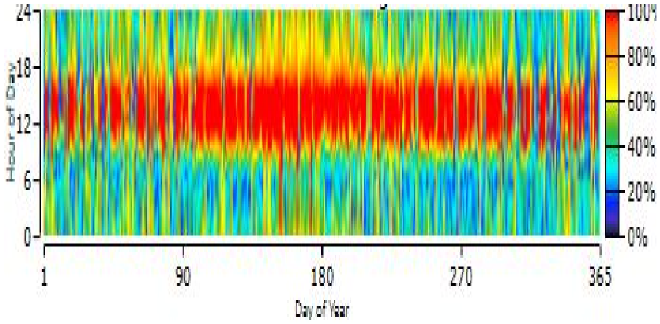

Figure 20: State of Charge of Battery Units of Design III

4.3.4 Emission Results

HOMER determines the emissions factor (kg of pollutant emitted per unit of fuel consumed) for each pollutant. After the simulation, it calculates the annual emissions of that pollutant by multiplying the emissions factor by the total annual fuel consumption. Carbon emissions represent the lion's share from the total emissions types emitted by DEG. The total amount of carbon emissions for each hybrid system design in kg/ year is shown in Table 5.

Table 5: CO_2 Emission Results

Parameter	Design I	Design II	Design III
CO_2 Emissions	4,367,332	5,621,835	3,266,470

5. DISCUSSION OF RESULTS

Following the presentation of design simulation results, an economic comparison, environmental and social effects of the three hybrid systems are discussed in this section for the purpose of selecting the optimal electric power generation system that serves the load optimally in the sense of low cost of COE and NPV.

5.1 Economic Comparison

The yearly electricity bill of the University of Jordan is around 5 million USD [11]. The NPC considering the time value of money at i=10% for 25 years which yields NPC 47.4 million USD by as per equation (1) [13].

$$P = A\left[\frac{(1+i)^N - 1}{i(1+i)^N}\right] \quad (1)$$

where P is the NPC, A is the annual electricity bill in USD, N is the number of years, and i is the interest rate.

Note that the obtained number of the NPC (at 10%) which is equal to 47.4 million USD is higher than the NPC of the three designs that have been discussed.

To calculate the COE, HOMER divides the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total electric load served as per equation (2) [12].

$$COE = \frac{C_{ann,tot} - C_{boiler} H_{served}}{E_{served}} \quad (2)$$

where, $C_{ann,tot}$ is the total annualized cost of the system in USD/yr, C_{boiler} is the boiler marginal cost in USD/kWh, H_{served} is the total thermal load served in kWh/yr, E_{served} is the total electrical load served in kWh/yr.

The second term in the numerator is the portion of the annualized cost that results from serving the thermal load. In systems, such as wind or PV, that do not serve a thermal load the parameter $H_{thermal}$ is set equal to zero.

The IRR is a critical parameter because this single number contains a strategic meaning and an indication of when the investment will recover its capital cost and its expenses. If IRR is high, then it indicates that the most revenues are at the beginning of the investment, and if it is low, then the recovery of the investment is at the last years of the investment.

The simple payback period ignores the time value of money and all cash flows that occur after θ (the year at which the revenues just equal the expenses). The discounted payback period is calculated so that the time value of money is considered. Note that the discount payback period is always longer than the simple payback period.

The optimal hybrid system economically has the lowest NPC and COE, higher IRR, and lower Discount payback period. Consequently, the PV-Grid hybrid system (design II) satisfies the condition of selection. Design II has NPC of10.5 million USD,COE of 0.0331USD/kWh, IRR of 80.9%,1.4 years discount payback period, and 12.3 million USD capital (initial) cost.

5.2 Environmental Effects

Nowadays, the global focusing on the environment becomes higher every day, because there are too many problems that appeared such as global warming, increasing the water sea level, or even the damaging Ozone Layer. IPCC (Intergovernmental Panel on Climate Change) has considered electricity generation the biggest carbon emitter, so using renewable energy resources is important for the environment [14]. From the emission results, we notice that both Design I and Design III have the same number of DEGs but the emissions from Design III are lower than the emissions from Design I because Design III has a wind turbine beside the DEGs which makes sense. Also, note that any carbon emissions related to the second design are the responsibility of the grid not the responsibility of the institution, and because of the lack of reliable and exact data for the emission categories, we used the default data of the HOMER software. This explains the high value of emissions in the second design. note that the HOMER software is an American software and the grid emission default based on the U.S. electrical grid which depends 30.4% on the coal to generate electricity which explains the high value of emissions in the second design (PV-grid) [15].

The amount of CO_2 emission of the stand-alone DEG system is 16,516,869 kg/yr (special case design was done using HOMER software).By using equation (3), the overall CO2 emissions of the PV-Grid hybrid system were reduced by 66% as compared with the emissions of only the DEG system. Similarly, CO2 emissions of the PV-Diesel-Battery hybrid system were reduced by 74 % and 80.2% for the PV-Wind-Diesel-Battery hybrid system. The more DEGs included, the more CO_2 emissions are produced.

$$\%\,Reduction = \frac{Emiss_{DEG} - Emiss_{Design\ x}}{Emiss_{DEG}} \qquad (3)$$

where $Emiss_{DEG}$ is the total emissions of a stand-alone DEG system, $Emiss_{Design\ x}$ is the total emissions of a single design, and x= I, II, or III.

5.3 Social Effects

Social habits and the things in what people are convenient with is important to make sure the local's acceptance to the project, for example, the wind turbine creates much noise for human and animals, even more, some big birds can cause severe damage for the fan blades which means that the wind turbine will inter to unstable rotation can leads do falling for the entire turbine and causing disaster if it is happening in a crowding area. Also, the installation of wind turbines needs a wide surface area which is expensive and unaccepted for the situation of the University of Jordan project. In addition to this, the DEG is not accepted in cities for ordinary or continuous usage because of the emission and noise, but DEG usage is common for emergencies. As a result, in the social discussion, design II (PV-grid hybrid system) will win since it contains neither DEG nor wind turbines.

6. CONCLUSION

Three hybrid power generation systems, namely, PV-Diesel-Battery, PV-Grid, and PV-Wind-Diesel-Battery hybrid systems were designed using HOMER software to choose the optimal power generation system which has the lowest NPC and COE to serve the university demand. The simulation results have shown that the NPC and COE for the PV-Diesel-Battery hybrid system were 21.7 million USD and 0.1 USD/kWh respectively, for the PV-Grid hybrid system were 10.5 million USD and 0.0331 USD/kWh respectively, and for the PV-Wind-Diesel-Battery hybrid system are 24.5 million USD and 0.113 USD/kWh respectively. Consequently, it can be concluded that the PV-Grid hybrid system gives the lowest NPC and COE as compared with the other two hybrid configurations or with the only grid-connected system. Also, the overall CO_2 emissions of the PV-Grid hybrid system were reduced by 66% as compared with the emissions of only the DEG system. Similarly, CO_2 emissions of the PV-Diesel-Battery hybrid system were reduced by 74 % and 80.2% for the PV-Wind-Diesel-Battery hybrid system. Therefore, there is no doubt that the PV-grid hybrid system is an excellent alternative power source for supplying the load and its benefits superseded the conventional power grid supply system.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support and facilities provided by The University of Jordan.

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