Innovative Systems Design and Engineering
ISSN 2222-1727 (Paper) ISSN 2222-2871 (Online)
Vol.8, No.1, 2017

Techno-Economic Analysis of Hybrid Renewable Energy Systems for Electrification of Rustic Area in Egypt

Mohamed Mahmoud Samy[1a*]

[1]Electrical Engineering Department, Faculty of Industrial Education, Beni-Suef University, Beni-Suef, Egypt.

[a] Electrical Engineering Department, Faculty of Engineering, Al-Baha University, Al-Baha, KSA.

Abstract:

Hybrid Power Systems (HPSs), particularly renewable energy-mix systems, use a wide variety of enabling technologies to overcome the difficulties associated with Renewable Energy (RE) resource variability in both standalone and grid-connected systems. According to the Egyptian national program towards reaching the 2020 objectives together with the continuous declination of the RE generation cost, extensive development and deployment of RE are witnessed from the government, academia, utilities and industry in Egypt. Therefore, this paper mainly aims at highlighting the potential of RE-hydrogen concept application for rural electrification in the small villages in Egypt in comparison with batteries. After introducing the comprehensive literature review that demonstrates the advantages and drawbacks of the RE standalone systems that mostly necessitates an Energy Storage System (ESS) support.

The optimal.conomic design of the HPS that feeds the required electric load of the small Mansheat Taher village at Beni-Suef Governorate, Egypt is considered. For this purpose, five different HPS configurations are studied such as: PV-wind-battery, PV-Fuel Cell (FC), wind-FC, PV-wind-FC, and PV-wind-battery-FC systems. The models of various systems are optimally designed, sized based on the daily data for energy availability and the demand using HOMERTM software. From the viability analysis of the simulation results, HPS system of xxxxxxx that provides a total net present cost of $1,233,317 is considered the most economic and feasible option. The cost of energy is 0.1424 $/kwh with a required initial capital of $916,728.

A case study area, Monshaet Taher village at Beni-Suef Governorate, Egypt with (29° 1' 17.0718"N, 30° 52' 17.04"E) is identified for economic feasibility in this work. HOMER optimization model plan was designed with annual average solar radiation scaled of 5.93 (kWh/m2/day), annual average wind speed for the location is 4.92 m/s.

Keywords: Batteries, Energy Storage; Fuel Cells; Hybrid System; Renewable Energy; Rural Electrification.

1. Introduction:

The World Bank organization has reported that, Egypt is the third largest population country in Africa and it is the third highest gross national income (GNI) [1] comparing other countries. The economy of Egypt is still suffering from problems since the revolution of 2011 as the country experienced a sharp decline in tourism revenue and foreign direct investment, according to the International Monetary Fund (IMF) [2]. Egypt faces more challenges in providing sufficient energy sources, especially oil and natural gas, which amounted to a reliable 95% of the total Egypt's energy needs. Reserches and studies show that, Egypt possesses a reserve of s due to rapid rsify its energy sources to meet the fuel deficit, which could make Egypt always been a net importer of fuel, which affects the reserves foreign exchange in the central bank [3].

The generating capacity of Egypt, as of May 2015, was about 31.5 Giga Watts, slightly higher than the expected creast demand of power in 2015 of 30 GW, related to Middle East Economic Survey (MEES) [4]. About 88.4% of Egypt's electricity is fueled by fossil fuel (natural gas, with the remainder being fueled by petroleum and renewable energy (mostly hydroelectricity) [5]. Egypt has a great potential for renewable energy: the coastal areas on the Red Sea are among the world's finest wind regions and the large desert areas in the country enjoy intense solar radiation. The Government, moreover, has supported the development of renewable energy for a long time. The Government is clearly obliged to further developing renewable energy and has set the – ambitious – target that by 2022 renewable energy will supply 20% of the growing electricity demand in Egypt. In addition, the promotion of renewable energy will help to develop an indigenous renewable energy industry. In December

2014, Egypt has enacted a new Renewable Energy Law (Law 203/2014) which is a major step towards establishing a comprehensive legal framework for renewable energy projects [6].

2. Previous Studies in Egypt

Different distributed generation (DG) systems including photovoltaic, fuel cell and wind turbine forming a DC micro-grid are modeled, controlled and simulated [7]. The DC micro-grid is simulated in grid-connected mode under different operating conditions. An energy system comprising three energy sources, namely PV, wind and fuel cells, is proposed [8]. Fuzzy logic control is employed to achieve maximum power tracking for both PV and wind energies and to deliver this maximum power to a fixed dc voltage bus. The fixed voltage bus supplies the load, while the excess power feeds the water electrolyzer used to generate hydrogen for supplying the fuel cells.

A hybrid Photovoltaic fuel cell generation system employing an electrolyzer for hydrogen generation is designed and simulated and is applicable for remote areas or isolated loads [9]. The system incorporates a controller designed to achieve permanent power supply to the load via the PV array or the fuel cell, or both according to the power available from the sun. [10] Presents a hybrid wind/FC renewable energy utilization scheme for electrical energy supply to Village/Island or remote areas. The integrated renewable scheme utilized a multi regulator error driven coordinated controller to ensure effective energy utilization, common DC and AC bus stabilization, enhanced power quality and near maximum energy utilization under varying operating conditions and/ or load excursions. The design of an optimum efficient cost PV-wind-fuel cell hybrid system that meets a known electric load of small scale brackish reverse osmosis desalination unit and a tourism motel [11].

3. Description of the proposed systems

In this work, Monshaet Taher village at Beni-Suef governorate, has been selected for the development of an integrated renewable energy system in Egypt. Beni-Suef is an important agricultural trade center on the west bank of the Nile with total area estimated of 7,169 km. The total area of the village is about 1463 acres, cultivated area represents according to a statement of the Ministry of Agriculture 1447 acres, representing 98.6% of the area of the village. In Monshaet Taher village, there are about 450 households with 7000 of local people [12]. Farming is the dominant source of income for rural households in this region and the remaining primary income source is shop owner, petty trader and casual labor. The renewable energy project can change the lifestyle of the people of the Monshaet Taher.

The objective of this paper is to design an optimal economic power renewable energy system that feeds the required electric load of Monshaet Taher village. The models have been designed to provide an optimal system configuration based on daily data for energy availability and demands. Five renewable energy power systems are presented in this paper to select the most optimum one of them which is PV-wind-battery, PV-fuel cell, wind-fuel cell, PV-wind-fuel cell, and PV-wind-battery-fuel cell hybrid systems as shown in Fig. 1. The system combines a water electrolyzer and a hydrogen storage tank to supply the fuel cell stack with hydrogen. The DC power required for hydrogen generation is supplied through the DC bus during surplus PV/wind power. The generated hydrogen is stored in tanks to be used by the fuel cells when the PV and wind energy sources fail to supply the load demand [8].

Technical and economic analyses were performed using the National Renewable Energy Laboratory's (NREL's) HOMER software tool that facilitates optimum design of renewable hybrid systems. HOMER simulates system operation during its entire lifetime, whereas required input data refer to capital expenses, operation and maintenance and replacement costs [13].

Monshaet Taher is a village which electricity grid has been already connected with low reliability so the capacity and continuity of electricity supply is limited. The village consists of 450 houses and others public affairs. The average load of the village is approximately 3102 kWh/day (or 129 kW) with 236 kW peak and has a load factor of 0.548 (which equates to the average load divided by the peak load, the load factor is 129 kW / 236 kW = 0.548).

4. Hourly load demand curves

Load demand curves have been performed by utilizing a logical assumption suggesting that load demand varies in time, depends on the inhabitant presence in a room; that is why load demand curves are irregular and quite choppy over the time. Fig. 3 exhibits the typical profile of the electrical load which is used in the case study, while Fig. 4 shows the Monthly average load of the study area.

5. Renewable Energy Resources

5.1.1. Solar radiation:

The solar resource used for Monshaet Taher village at a location of 29°2' N latitude and 31°6' E longitude was taken from NASA Surface Meteorology and Solar Energy website [14]. The annual average solar radiation was scaled to be 5.93 kWh/m²/Day. The scaled data of global radiation and Clearness index of the study area is shown in Fig. 5.

5.1.2. Wind resource

The ten years average monthly wind speed data was taken from the NASA resource website based on the location of the study area location [14]. The annual average wind speed for the location is 4.92 m/sec. The scaled data of wind resource of the study area is shown in Fig. 5 while the characteristic wind speed distribution is shown in Fig. 6.

6. Hybrid System Modeling

The optimal system combination will lead to the optimal system design with the lowest leveled cost of energy. HOMER software application is used to design, evaluate technically and financially the options for the proposed power systems. HOMER can optimize the system configuration, and perform sensitivity analyses, therefore the designer can make the right decision when the supplying load is needed to optimize with minimization of energy cost [13].The optimization process consists in finding the optimal value of decision variable chosen by the designer and over which he has optimal control and for which HOMER can consider multiple possible values in its optimization process.The input data including solar, wind resource data, electricity usage of the Monshaet Taher village and the components of the hybrid system are put in HOMER software tool built as a model plan. The capital, replacement and O&M costs of the various system components have been given in Table 1.

6.1. Photovoltaic panels

The input data for the simulation model applied involved the following parameters: 20 years lifetime of the module and 20% ground reflectance. A derating factor of 0.9 was applied to the electric production from each panel. This factor reduces the PV production by 10% to approximate the varying effects of temperature and dust on the panels. The panels were modeled as fixed and tilted south at an angle equal to the latitude of the site (29.03°). Photovoltaic sizes considered 0 to 1000 kW (step = 50 kW).

6.2. Batteries

In this analysis, we used the Trojan IND29-4V Deep-cycle batteries used in off-grid and unstable grid applications are heavily cycled at partial state of charge (PSOC). Operating at PSOC on a regular basis can quickly diminish the overall life of a battery, which results in frequent and costly battery replacements. Ah maximum capacity of the battery is 2166, 81% round trip efficiency, and 20% minimum state of charge. Lifetime of the batteries is 20 years, and lifetime throughput is 10,900 kWh [13, 15]. Number of batteries considered 0 to 250 (step =25).

6.3. Wind generator

The power curve of the wind turbine (serving as a function of wind speed of the generic 10 kW wind generator) is shown in Fig. 7; it has a rated capacity of 10 kW and the number of wind generators is to be considered as 100.

6.4. Electrolyzer

Water electrolyzer consists of several cells connected in series. Two electrodes of the electrolyzer are separated by an aqueous electrolyte or solid polymer electrolyte. Electrical current through the electrolyzer enables the de-composition of water into hydrogen and oxygen. The replacement cost of the electrolyzer is assumed to lower than the capital cost because some components included in the capital cost have longer life time than the stack itself [17].

6.5. Fuel cells

A fuel cell is an energy conversion device, which converts the chemical energy of a fuel and oxidant, often hydrogen and oxygen, to electrical energy fuel cells are similar to batteries, however, unlike battery a fuel cell must be continuously provided with fuel, rather than deriving energy from materials contained within the cell, and the products of the electrochemical reaction must be removed the cell. The operating efficiency of fuel cell approaching about 60 % nearly twice the efficiency of conventional internal combustion engines [18]. The outputs of the fuel cell are DC current and water. Fuel cells are very attractive option to be used with intermittent sources of generation like the PV. The feasibility of fuel cell in coordination with PV systems has been successfully demonstrated for both grid-connected and stand-alone applications [19]. A Proton exchange membrane (PEM) fuel cell was chosen because of its passive operation, high efficiency, silent and its ability to provide power quickly from a standby configuration [16].

6.6. Hydrogen Storage

Hydrogen as an energy carrier must be stored to overcome daily and seasonal discrepancies between energy source availability and demand. Hydrogen storage has an economic advantage over lead acid batteries for long-term storage. Currently, pressurized tanks are still the most cost-effective means of hydrogen storage for most applications [20]. It is known that a stand-alone energy system needs a storage system to provide energy for the cases of inappropriate weather conditions, instantaneous overload conditions, or demand for energy after sunset [21].

7. Simulation Results

The simulation results of the proposed five power system configurations are displayed in Table 2. The first power system, (PV-Wind-Battery) offers the lower NPC and Leveled cost of energy (LCOE). On the other hand, the fourth power system, (PV-Wind- Fuel Cell) has higher Initial Capital Costs, NPC and LCOE. By adding batteries to power system five, (PV-Wind- Fuel Cell), it leads to 41% in NPC and 39% in LCOE less than power system four, and then power system five becomes the second best optimal power system.

According to the results of the optimization process, the optimal power system comprises a 226 kW PV array, a 230 kW wind turbine, a 166 kW converter and 189 batteries. The proposed system gives a total net present cost of $1,233,317 and the cost of energy is 0.1424 $/kWh while the initial capital required is $916,728.

As shown in Fig. 9 (a) and (b) the load is supplied with a hybrid system comprising of PV array, wind generator and battery storage. As shown in Fig. 9 (a), the PV/Wind hybrid system is able to provide energy approximately all time of the year. It can be observed that, the load could be met right through the year .The battery state of charge varies between 35% and 76% as shown in Fig. 9 (b). For the selected system the PV panels operates for 4,384 hours (capacity factor 24.36%), produces 482,478 kWh per year, with total rated capacity of 226 kW. The leveled cost of solar electricity is 0.066 $/kWh. The 10kW-Wind Turbine produce 346,524 kWh/year, with total rated capacity of 230 kW, operating for 8,760 hours/year (capacity factor of 17.20 %). The leveled cost of wind electricity is 0.059 $/kWh.

Fig. 9 presents the monthly data for PV-Fuel Cell hybrid system. It can be observed that the load could be met right through the year without excess energy. It clear from Fig. 10 that, the PV panels is the dominant producer of electricity, for the selected system the PV panels operates for 4,384 hours (capacity factor 24.36%), produces 1,562,075 kWh per year, with total rated capacity of 667 kW. The leveled cost of solar electricity is 0.064 $/kWh. While PEM fuel cells produce 365,855 kWh/year (capacity factor of 20.9 %), with total rated capacity of 200 kW, operating for 4510 hours/year, with fixed generation cost of 16.50 $/hr.

Fig. 10 presents the monthly data for Wind-Fuel Cell hybrid system. It can be observed that the load could be met right through the year with excess energy. It can be observed from Fig. 11 that the 10kW-Wind Turbine is the dominant producer of electricity, for the selected system the 10kW-Wind Turbine operates for 8,760 hours (capacity factor 17.2%), produces 1,506,628 kWh per year, with total rated capacity of 1000 kW. The leveled cost of wind electricity is 0.055 $/kWh. While PEM fuel cells produce 105,973 kWh/year (capacity factor of 8.57 %), with total rated capacity of 100 kW, operating for 4911 hours/year, with fixed generation cost of 14.3 $/hr. it can be noticed that this system uses 100 wind turbine while system1 used only 23 turbine.

It can be observed from Fig. 11 that the PV panels is the dominant producer of electricity, for the selected system the PV panels operates for 4,384 hours (capacity factor 24.361%), produces 1,061,518 kWh per year, with total rated capacity of 479 kW. The leveled cost of solar electricity is 0.0665 $/kWh. The 10kW- Wind Turbines produce 376,657 kWh/year, with total rated capacity of 250 kW, operating for 8,760 hours/year (capacity factor of 17.2 %). The leveled cost of wind electricity is 0.059 $/kWh. While PEM fuel cells produce 207,294 kWh/year (capacity factor of 11.8 %), with total rated capacity of 200 kW, operating for 5,006 hours/year, with fixed generation cost of 8 $/hr.

Fig. 12(a) presents the monthly data for PV-Wind-Fuel Cell - Battery hybrid system. It can be observed that the system easily satisfies loads through the year. The battery state of charge varies between 40% and 86% as shown in Fig. 12(b). For the selected system the PV panels operates for 4,384 hours (capacity factor 24.36%), produces 579,489 kWh per year, with total rated capacity of 272 kW. The leveled cost of solar electricity is 0.066 $/kWh. The 10kW-Wind Turbine produce 376,657 kWh/year, with total rated capacity of 250 kW, operating for 8,760 hours/year (capacity factor of 17.2 %). The leveled cost of wind electricity is 0.059 $/kWh. While PEM fuel cells produce 49,472 kWh/year, with total rated capacity of 100 kW, operating for 785 hours/year, with fixed generation cost of 4 $/hr.

8. Conclusions

Hybrid renewable energy Systems are going to play a key role as the global electricity networks slowly minimize their dependence on fossil fuels. This is especially valid in the case of developing countries including

Egypt. Using a fuel cell to generate electricity induces a low efficiency but allows building a quiet energy generator consuming no materials.

In this paper, the design of an optimum–efficient cost hybrid renewable energy system that meets a known electric load of small village in Egypt was developed. The computer pro-gram (HOMER Pro.) solves the optimization problem. In addition, the comparison between the five suggested different power system configurations was illustrated with details. These systems are compared with respect to the total net present cost (NPC) and leveled cost of energy. The PV-wind- battery hybrid system, offers the much lower NPC and LCOE. On the other hand, PV-Wind- Fuel Cell hybrid system has higher initial capital costs, NPC and LCOE. The high PV-wind-fuel cell system cost over PV- wind-buttery system is due to the high capital cost of fuel cell system and electrolyzer compared to battery. Therefore, the major obstacle in using hydrogen as a storage medium is the high cost associated with it.

9. References:

[1] World Bank database, "http://data.worldbank.org/country/Egypt-Arab-republic", accessed November 2015.

[2] Egypt International energy data and analysis, http://www.eia.gov/beta/international/analysis.cfm?iso=EGY, accessed November 2015.

[3] Renewable Energy Feed-in Tariff Projects Regulations 2014, http://egyptera.org/en/kwa3d%20tanzmia.aspx"", accessed November 2015.

[4] Middle East Economic Survey (MEES), "Egypt adds Power Ship to Short-Term Plan, Lines up Loans for EEHC," (May 8, 2015), Vol. 58, issue 19.

[5] Business Monitor International (BMI) Research, Egypt Power Report Q2 2015, (March 2015), pages 12-15.

[6] "Investing in Renewable Energy in Egypt " January 2015 [on line]

[7] Ahmad Eid, "Utility integration of PV-wind-fuel cell hybrid distributed generation systems under variable load demands", Electrical Power and Energy Systems 62 (2014) 689–699.

[8] Thanaa F. El-Shatter, Mona N. Eskander, and Mohsen T. El-Hagry, "Energy flow and management of a hybrid wind/PV/fuel cell generation system", Energy Conversion and Management 47 (2006) 1264–1280.

[9] Th.F. El-Shatter, M.N. Eskandar, and M.T. El-Hagry, “Hybrid PV/fuel cell system design and simulation”, Renewable Energy 27 (2002) 479–485.

[10] Mohamed A. H. El-Sayed, Adel M. Sharaf , " Hybrid Wind-Fuel Cell Renewable Energy Utilization Scheme for Village Electricity" , Proceedings of the 14th International Middle East Power Systems Conference (MEPCON’10), Cairo University, Egypt, December 19-21, 2010, Paper ID 132.

[11] Faten Hosney Fahmy, Ninet Mohamed Ahmed, Hanaa Mohamed Farghally, "Optimization of Renewable Energy Power System for Small Scale Brackish Reverse Osmosis Desalination Unit and a Tourism Motel in Egypt", Smart Grid and Renewable Energy, 2012, 3, 43-50.

[12] "Population data for a town or village according to the population estimates in 2014", Egyptian Central Agency for Public Mobilization and Statistics.

[13] Tom Lambert, Paul Gilman and Peter Lilienthal, "Micropower System Modeling with Homer",.Available: http://www.homerenergy.com/documents/Micropower System Modeling With HOMER.pdf [Accessed: 15- Feb- 2016].

[14] Eosweb.larc.nasa.gov, "NASA Surface meteorology and Solar Energy Location", [Online].Available:https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov. [Accessed: 10- Feb- 2016].

[15] http://www.trojanbattery.com/product/ind29-4v/ [Accessed: 10- Apr- 2016].

[16] Omar Hazem Mohammed, Yassine Amirat, Mohamed Benbouzid, and Adel Elbast. "Optimal Design of a PV/Fuel Cell Hybrid Power System for the City of Brest in France", IEEE ICGE 2014, Mar 2014, Sfax, Tunisia. pp.119-123, 2014.

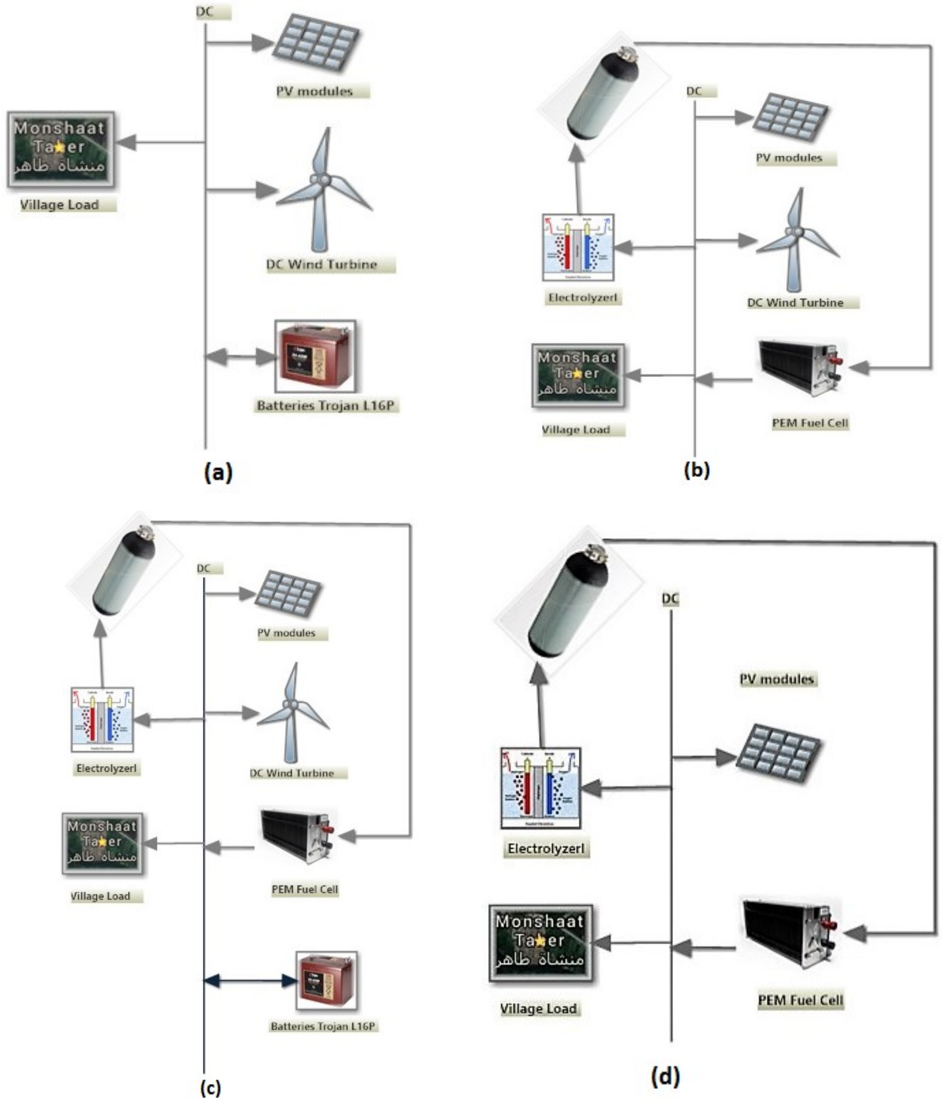
[17] M. J. Khan and M. T. Iqbal, "Pre-Feasibility Study of Stand-Alone Hybrid Energy Systems for Applications in Newfoundland," Renewable Energy, Vol. 30, No. 6, 2005, pp. 835-854.

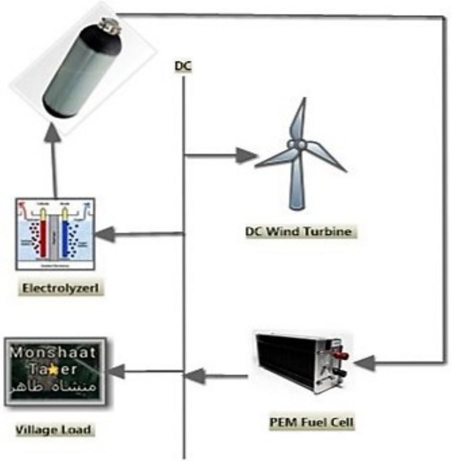
[18] Fuel Cell Handbook, 6th edition., National Energy Technology Lab, U.S. DOE, Pittsburgh, PA, 2002.

[19] S. Rahman and K. Tam, IEEE Transactions on Energy Conversion 3 (1), 1988, pp. 50-55.

[20] J. Cotrell, W. Pratt, NREL/TP-500-34648, 2003.

[21] E. Koutroulis, K. Kalaitzakis, “Renewable Energy” 28 (1), 2003, pp. 139-152.





(e)

Fig.1: Schematic diagram of the proposed system: (a) PV-wind-battery hybrid system, (b) PV-wind-fuel cell hybrid system, (c) PV-wind-battery-fuel cell hybrid system, (d) PV-fuel cell hybrid system, and (e) wind-fuel cell hybrid system.

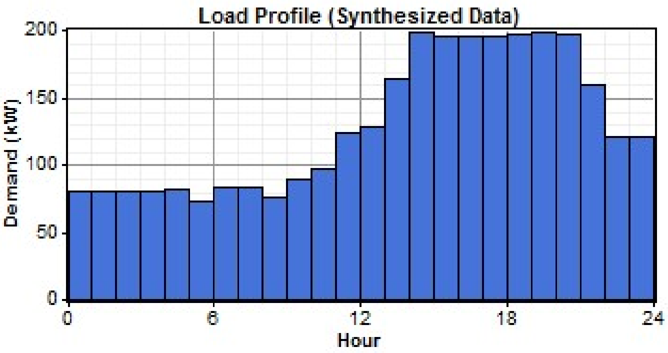


Fig. 2: Daily load of the study area

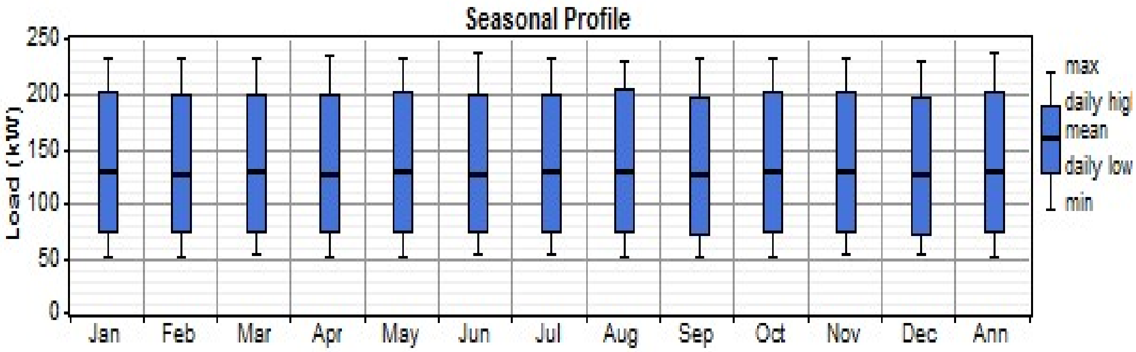


Fig. 3: Monthly averages load of the study area

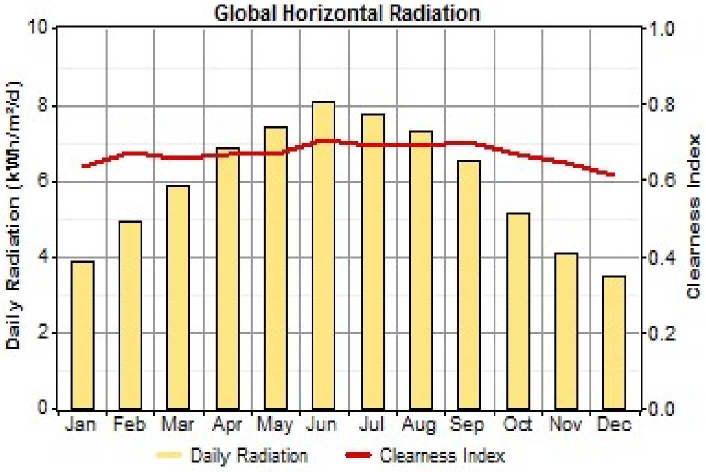


Fig. 4: Solar energy profile of the study area

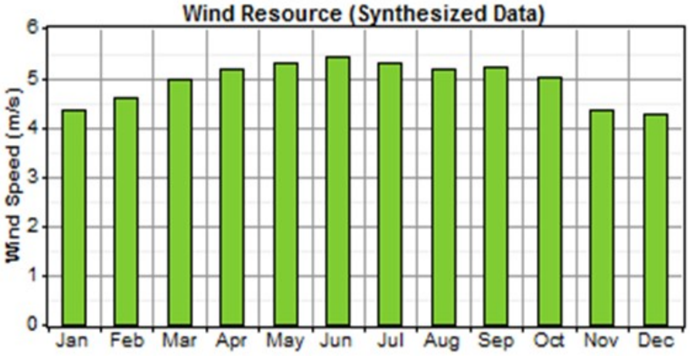


Fig. 5: Wind energy profile at the selected village

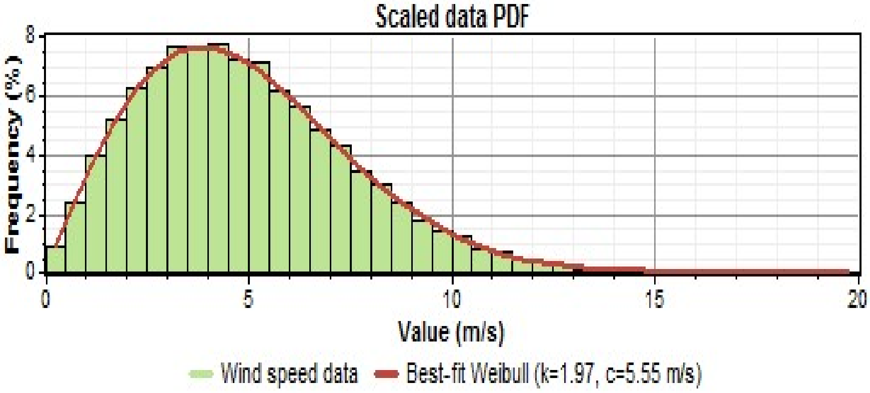


Fig. 6: Wind speed distribution at the selected village

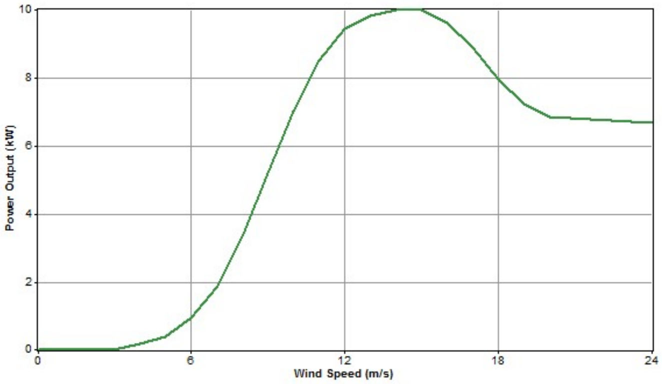
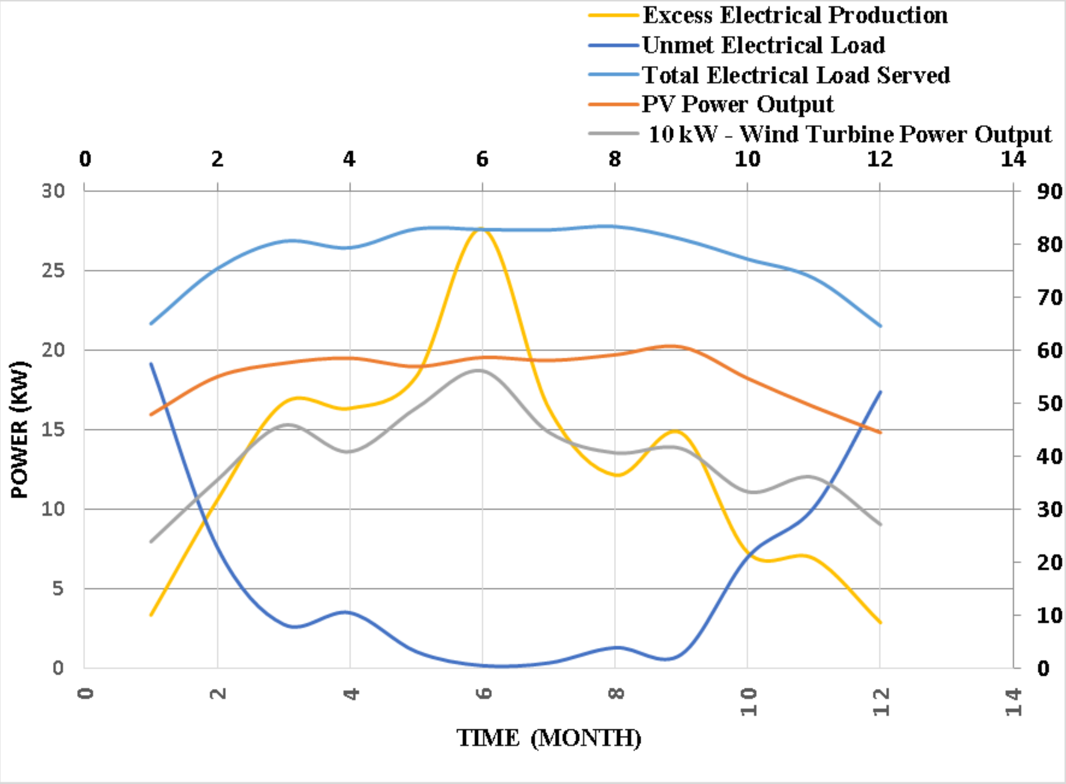
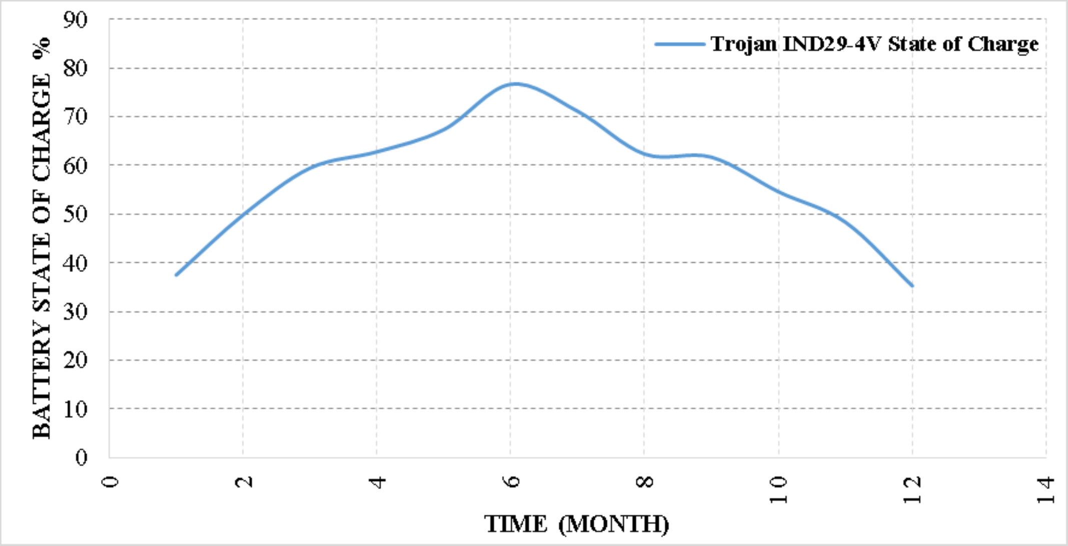


Fig. 7: The wind turbine power curve



(a)



(b)

Fig. 8: Monthly data for power system 1.

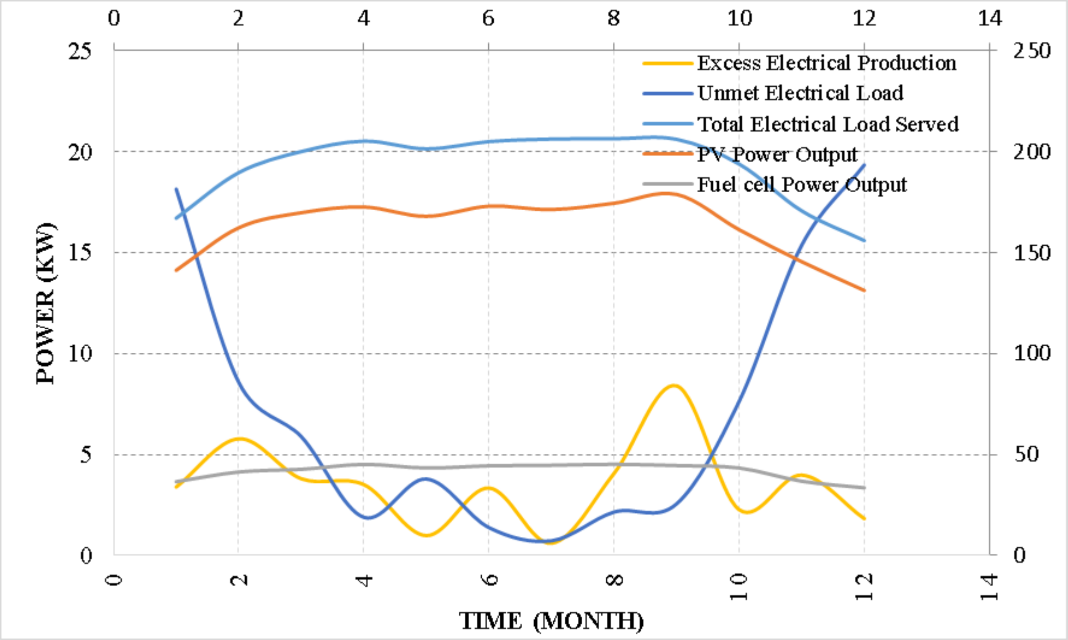


Fig. 9: Monthly data for power system 2.

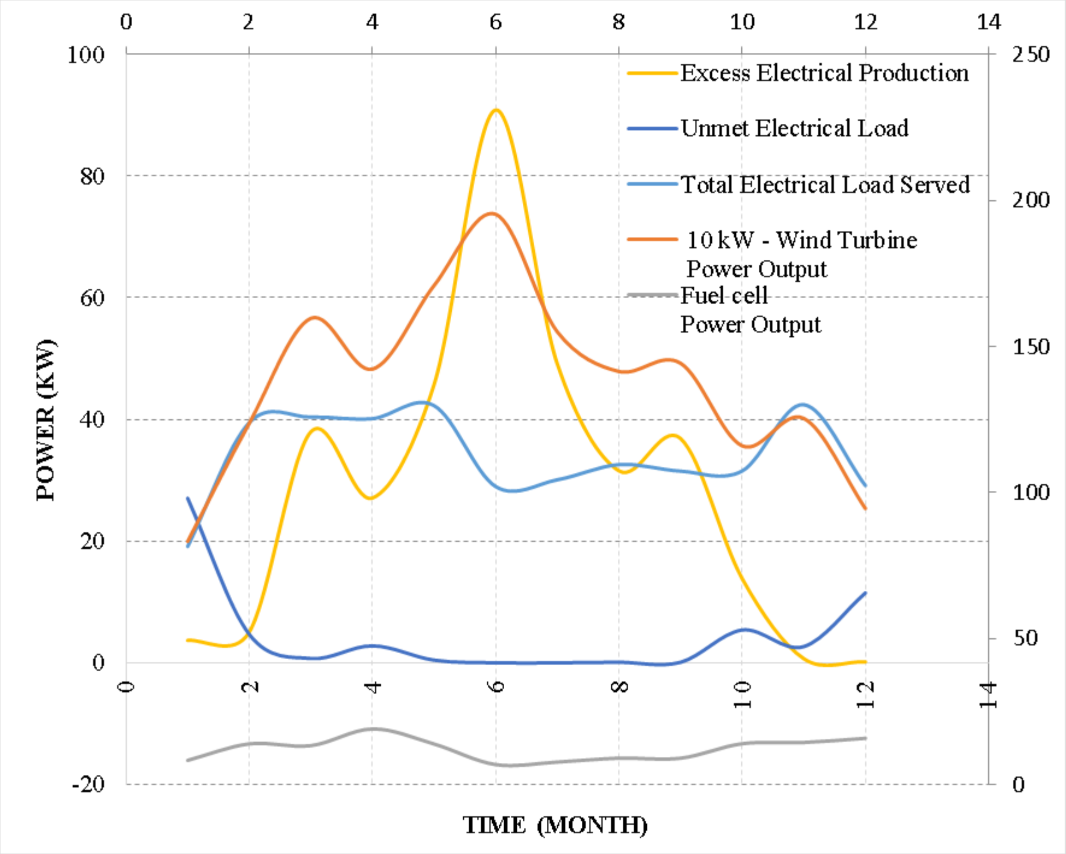


Fig. 10: Monthly data for power system three.

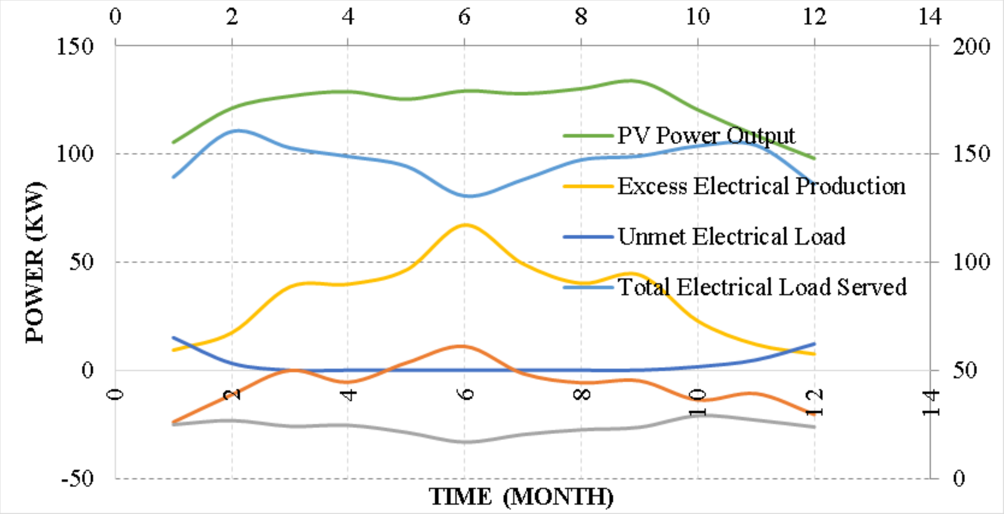
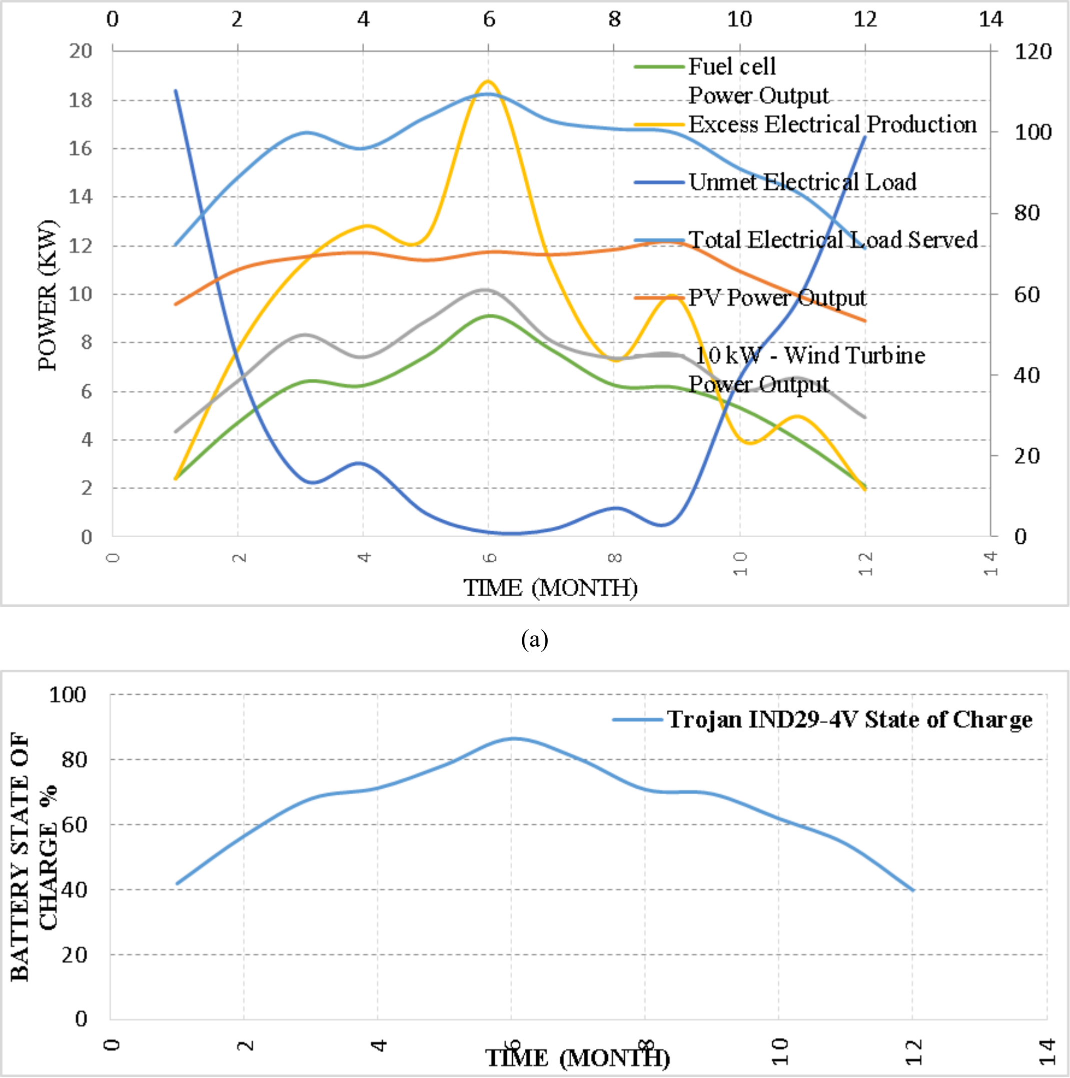


Fig. 11: Monthly data for power system four.



(a)

(b)

Fig. 12: Monthly data for power system five.

Table1: Cost details of the various equipment used in the proposed scheme

		Capital ($)	Replacement ($)	O&M ($/yrs.s)	Lifetime (yrs.s)
PV module	1 kW	1,500	1,350	5	20
Wind Turbine: generic 10 kW	1 piece	10,000	9,500	50	25
Battery: IND29-4V [15]	1 piece	275	275	3	10
PEM fuel cells [16]	5 kW	3,000	2,500	0.08 $/(h.kW)	40,000 h
Electrolyzer	3 kW	2,000	1,800	10	20
Hydrogen tank	1 kg	500	500	5	20
Converter [13]	3 kW	1,500	1,300	5	15

Table 2. Optimization sizing results.

Item	Power System 1 **PV-Wind-Battery**	Power System 2 **PV-Fuel Cell**	Power System 3 **Wind-Fuel Cell**	Power System 4 **PV-Wind-Fuel Cell**	Power System 5 **PV-Wind-Fuel Cell-Battery**
Optimization Sizing Results	• 226 kW PV Array • 23 x 10kW Wind turbine • 189(63*3) strings Trojan IND29-4V • 166 kW Converter	• 667 kW PV Array • 200 kW Fuel cells • 161 kW Converter • 500 kW Electrolyzer • 120 kg Hydrogen tank	• 100 x 10kW Wind turbine • 100 kW Fuel cells • 156 kW Converter • 100 kW Electrolyzer • 80 kg Hydrogen tank	• 497 kW PV Array • 25 x 10kW Wind turbine • 200 kW Fuel cells • 164 kW Converter • 300 kW Electrolyzer • 160 kg Hydrogen tank	• 272 kW PV Array • 25 x 10kW Wind turbine • 100 kW Fuel cells • 158 kW Converter • 165(55*3) strings Trojan IND29-4V • 100 kW Electrolyzer • 40 kg Hydrogen tank
Capital cost ($)	916,728	2,074,063	1,484,792	2,358,242	1,487,256
O & M ($)	86,001	305,634	578,852	490,521	154,660
Replacement cost ($)	336,557	898,146	368,811	615,847	394,944
Net Present cost ($) (NPC)	1,233,317	3,031,109	2,357,260	3,224,402	1,899,946
Leveled cost of energy (LCOE) ($/kwh)	0.1424	0.356	0.2675	0.3588	0.2184
Production (kWh/year)	• PV array: 58.2% • Wind turbines: 41.8%	• PV array: 79.54% • Fuel cells: 20.46%	• Wind turbines: 95% • Fuel cells: 5%	• PV array: 64.51% • Wind turbines: 22.89% • Fuel cells: 12.6%	• PV array: 57.63% • Wind turbines: 37.46% • Fuel cells: 4.92%
fixed generation cost (fuel cells) ($/hr)	-	16.50	14.3	8	4
Carbon Dioxide Emissions	0 kg/yrs.	-224.22 kg/yrs.	-64.948 kg/yrs.	-127 kg/yrs.	-30.319 kg/yrs.