Chapter

Economic Analysis of Stand-Alone Hybrid Wind/PV/Diesel Water Pumping System: A Case Study in Egypt

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Abstract

The design and evaluation of a stand-alone hybrid renewable energy system for pumping underground water for small farm irrigation is presented. Given environmental conditions, system specifications and daily load demand data, the optimal size of main system components is obtained using a sizing algorithm. Different renewable energy systems are compared using yearly simulations, on hourly base via specialized commercial software simulation packages PVSYST and HOMER, to simulate the system performance and to reach the optimum configurations based on the objective criteria. The criteria used in economic optimization are the net present cost and the cost of energy, with the percent of the capacity shortage. The following systems can be compared: PV only, PV with horizontal axis wind turbine, PV with vertical axis wind turbine, and PV with horizontal axis wind turbine and diesel generator and diesel generator only. The simulation also was carried out for different load patterns for optimum operation. The study was illustrated for climatic conditions of an isolated area in El-Tour City, Sinai, Egypt. The installed 3.42 kW PV water pumping system for irrigation purposes in the same site was also described.

Keywords: water pumping, stand-alone photovoltaic, wind turbine, hybrid system, diesel generator

1. Introduction

Egyptian Government has embarked an ambitious plan to develop new villages in the desert far from Nile River and Delta by reclaiming and cultivating 5 million acres over 5 years. The main challenge facing the government efforts is the inability of the current energy sources to provide those communities with the main infrastructures from energy and water to fulfill agriculture requirements. This is because these communities are small, scattered and located in the desert far from the electricity grid.

Hence, the Egyptian Government strategies targeted providing agriculture water requirements (pumping and irrigation) for new rural areas by applying renewable energy systems. Clean, renewable energies such as solar and wind are considered fast solutions to provide such communities with the energy necessities. The adopted approach has been motivated mainly by Egypt's location that is endowed with abundant solar energy, adequate average wind speed besides long sea shores and underground water.

Among the renewable energy options that are currently in wide use are solar photovoltaic (PV) and small wind turbines (WT) for water pumping and irrigation. Pumping water by mechanical wind mills in remote areas is an old technology [1, 2], and by renewable energy for the last few decades [3, 4]. Recently, many users of the water pumping have switched to solar energy via photovoltaic pumping for small systems, while for larger systems the diesel generations are still predominant for pumping water in Egypt [5]. Compared to PV systems and mechanical wind mills, small wind turbines are still in limited uses for water pumping systems in remote areas. Using hybrid photovoltaic/wind turbine (PV/WT) improves the water pumping reliability and increases the daily volume of the pumped water.

Different studies concerning the individual PV water pumping (PVWP) and wind turbine water pumping (WTWP) systems focused on the dynamic performance of these systems, in particular the match between water demand and water supply [6]. Benghanem et al. [7] compared the performances of different PVWP configurations for different hydraulic heads. Kelley et al. [8] studied the feasibility of PVWP systems for irrigation as a function of location, while Rehman and Sahin [9] investigated the technical and economic performances of several small WTs to provide water in Saudi Arabia.

The performances of PVWP and WTWP systems have also been compared. Kumar and Kandpal [10] assessed the potential of PVWP and WTWP systems for irrigation in India. Diaz-Mendez et al. [11] presented a simple methodology to compare PVWP and WTWP for irrigation of commercial greenhouses in Spain, Cuba and Pakistan. The study mainly focused on the economic comparison between PVWP and WTWP systems for irrigation for three specific locations with no indication to the match between water demand and water supply and the effect of water supply on the crop yield.

One of the most important limitation facing applications of renewable energies is that no individual source of solar or wind energies is capable of supplying both reliability and cost-effective due to the intermittent nature of them. Moreover, fluctuations in production and time-dependent are other challenges for renewable energy utilization. Flexible demand management [12–14], and smart energy management [15, 16], are useful, but they do not fully suffice in maintaining the balance between production and demand of electricity.

Hybrid PV/WT systems which optimize the contribution of solar and wind energy sources generation to provide continuous base requirements are the better solution of this problem. Using a hybrid solar/wind system helps to use solar energy in case of small wind speed and use wind energy in case of low solar radiation levels. Vick and Neal [17] analyzed the operation of solar PV and wind turbine as individual systems as well as a PV/WT hybrid system as off-grid system for pumping water. It was found that the hybrid system delivered more energy than only PV or wind by an amount of 28%. An additional buck/boost converter was also used as a controller to improve hybrid PV/WT water pumping system.

Research developments in the field of renewable energy-water pumping systems are reviewed by Gopal et al. [18]. They briefly reviewed hundreds of articles published in the water pumping systems and investigated five different system configurations with various types of energy; solar, wind, biomass, thermal and hybrid PV/WT. They concluded that using renewable energy (solar or wind or hybrid) highly reduces the dependence of conventional energy with good environmental impact.

According to the meteorological data measured for the city of Xanthi, Greece and their systematic design approach for three different systems for water pumping which are; PV, WT and hybrid PV/WT, Skretas and Papadopoulos [19] concluded that the performance of hybrid system was better than that of solar or wind only.

Ma et al. [20] introduced a new solution of the problem concerning the energy storage in the renewable energy systems, especially in standalone systems. In that work, an important and most traditional storage technology was used, this is the pumped hydro storage (PHS) with a standalone renewable energy system (solar-wind). They developed a mathematical model for the hybrid solar-wind system and applied according to the operating parameters on a case study to feed the required energy to a remote area in Hong Kong and examined its technical feasibility. Time dependent simulation results showed that the inherent fluctuations nature of the renewable energy sources can be effectively compensated by applying the PHS technology. This can provide a reliable and clean energy source power supply. They concluded that 100% of the energy autonomy in remote and rural areas can be achieved by pumped hydro storage-based hybrid renewable energy.

Many researchers used two public models for optimizing the hybrid renewable energy systems [21–23]. The first model was hybrid optimization model of electric renewable (HOMER) and the second was hybrid solar-wind system optimization model (HSWSO) [24]. The second model mainly used when using a storage battery bank in the hybrid system. The optimization process of the hybrid systems concluded that using a storage tank for water storage is more cost effective than using a storage battery bank in hybrid solar-wind system, due to the higher maintenance and operation costs of the batteries and vice versa for the water storage.

Yahyaoui et al. [25] optimized the design of a hybrid solar-wind-pumped storage system in standalone mode for an isolated area. The initial design process of the system's major components was presented, and optimized based on a techno-economic evaluation. The proposed design was evaluated using yearly simulations, on hourly base, performed by specialized commercial software, PVSYST.

A methodology for optimal sizing design and strategy control based on differential flatness approach was applied to the hybrid stand-alone PV/WT systems by Tégania et al. [26]. The aim was to find, according to life time of the system provided that the required load energy is completely supplied by the system, the optimal design of the system components that ensure minimum system costs. The problem formulation and the generic algorithm are used in optimization methodology to optimally configure the system, and the results are obtained using MATLAB/Simulink.

Therefore, the hybrid PV/WT system is usually installed to supply water in remote areas with considerably less costs and more reliable operation in case of inherent fluctuations of the renewable energy sources. The present study describes the main components of the installed stand-alone 3.42 kW PV water pumping system for irrigation purposes in El-Tour city, Sinai, Egypt. To investigate the feasibility of small, decentralized hybrid PV/WT system for water required for irrigation purposes, a theoretical comparison between different renewable energy systems for water pumping is carried out in the selected site based on using yearly simulations, on hourly base via specialized commercial software simulation packages PVSYST and HOMER, for optimum operation. The compared systems are: (i) PV only, (ii) PV with horizontal axis wind turbine (PV/HAWT), (iii) PV with vertical axis wind turbine (PV/VAWT), (iv) PV with horizontal axis wind turbine and diesel generator (PV/HAWT/D) and (v) diesel generator only. The criteria used in economic optimization are the net present cost, the cost of energy with the amount of unmet load or percent of energy shortage. The optimization process was carried out for different load patterns.

2. Installed PV/water pumping system

The installed small water pumping system is used to deliver water from a well for agriculture purposes in El-Tour city, Sinai, Egypt (latitude of 28.22° N and longitude of 33.61° E). The system consists of; the PV arrays, mechanical structure, pump controller and water pump.

Table 1 shows the site parameters; air temperature, wind speed and solar radiation levels, as average values. It is clear that the site has an annual average air temperature of 20.9°C with low values of wind speed reaches maximum value of 7 m/second which can be considered considerably low levels of wind speed. **Figure 1** shows irradiation levels on a horizontal and an optimally tilted surface (30°) in El-Tour, Sinai [27]. It is seen that the location has high irradiation levels all

Month (average values)	Air temperature (°C)	IR on optimally tilted surface ($Wh/m^2/day$)	Wind speed (m/second)
January	11.8	5650	4.70
February	12.7	6520	5.00
March	16.2	7760	4.70
April	21.0	7190	6.00
May	24.7	7200	6.50
June	26.8	7350	6.00
July	28.2	7320	5.90
August	28.1	7430	7.00
September	26.4	7290	6.00
October	22.8	7010	5.30
November	18.1	6100	4.90
December	13.4	5510	4.30
Annual	20.9	6860	5.53

Table 1.
Average air temperature, wind speed and solar radiation levels in El-Tour, Sinai.

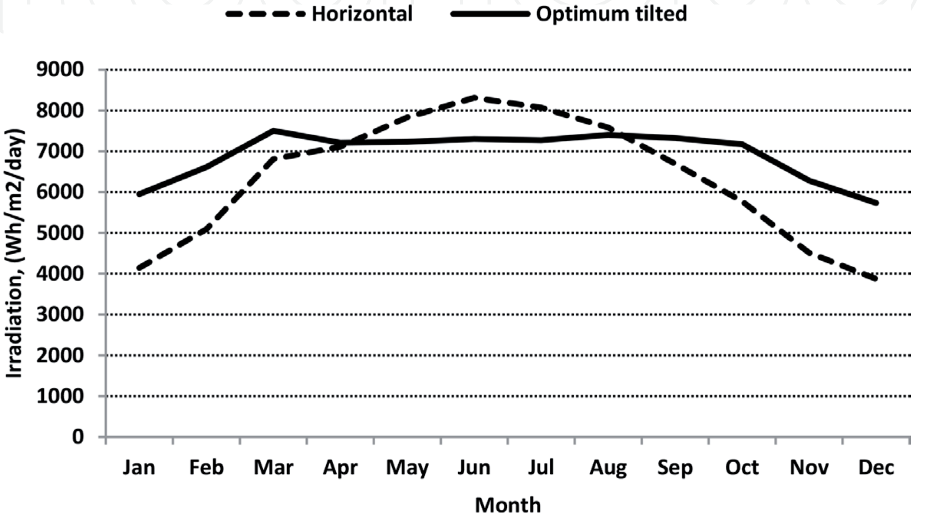

Figure 1.
Average irradiation levels on a horizontal and an optimally tilted surface in El-Tour, Sinai.

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over the year with an annual average of 6.86 kWh/m^2/day on an optimally tilted surface. This average value can be considered one of the highest irradiation levels all over the world.

Item	Specifications
Module power	190 W
Module cells	48
Number of modules	18
V_{OC}	29.76 V
I_{SC}	8.47 A
V_{MP}	24 V
I_{MP}	8.02 A

Table 2.
Characteristics of the PV system.

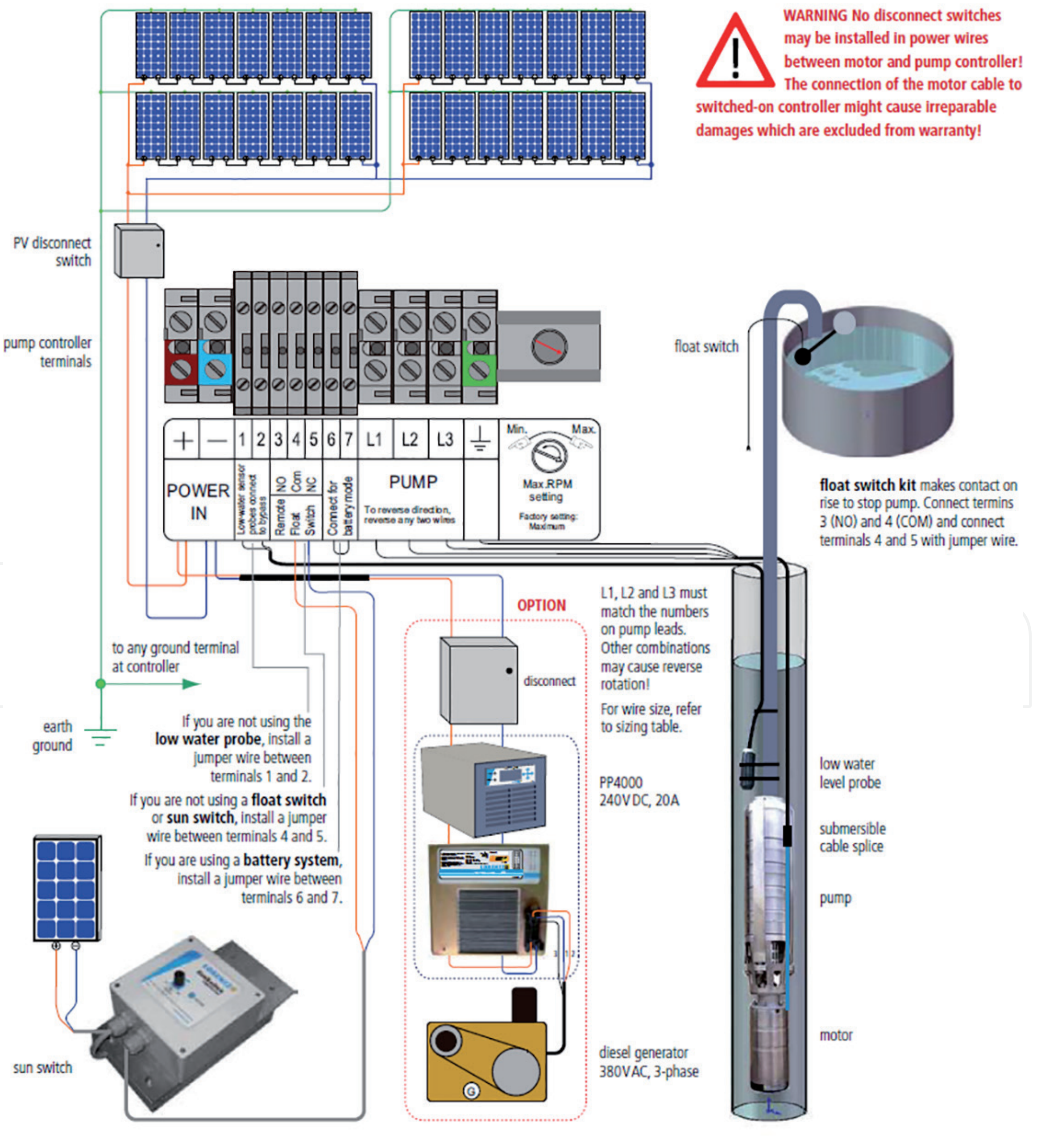

Figure 2.
Wiring diagram of the pump controller.

2.1 PV arrays

The PV system which is to drive the water pump motor, consists of 3.42 kW-PV power (18 PV modules) arranged in two parallel strings, each of them has nine modules connected in series. According to this arrangement, the PV system gives operating voltage about 216 V and 16 A at standard test conditions (STCs; 1000 w/m^2 of irradiance, 25° of module temperature and 1.5 AM). **Table 2** exhibits the characteristics of the used PV modules at STC.

2.2 Supporting structure

The supporting structure is used to fix the PV system facing south at tilt angle of 30° on the horizontal surface for optimum irradiation collection over the year. It is made of galvanized aluminum rods fitted via aluminum joints supported on eight concrete bases in order to ensure a stable and secure operation and to avoid vibrations or falling. This structure must withstand the environmental conditions of higher temperatures, humidity and wind speeds up to 15 m/second.

2.3 Pump controller

The pump controller is used to drive the pump electric motor via converting the input DC power from the PV arrays to the required AC power, voltages and currents suitable for the pump operation. The controller has many indicators to fully monitor the system operation. There are many protections features in the controller to safely start the pump at very low irradiation levels and protect it from vibrations and over load. **Figure 2** shows the pump controller and the wiring diagram, while **Table 3** illustrates the controller's parameter specifications.

2.4 Water pump

The water pump is solar-operated submersible pump with maximum flow rate of 7 m^3/hour and maximum head of 140 m. The pump has maintenance-free

Parameter	Power (kW)	Input voltage (V)	Optimum voltage (V)	Motor current (A)	Efficiency (%)	Ambient temperature (°C)	Enclosure class	Weight (kg)
Specification	4	Max 375	238	Max 15	98	−30 to 50	IP54	9

Table 3.
Parameters of the pump controller.

Parameter	Specification
Rated power	3.5 kW
Efficiency	92%
Motor speed	900–3300 rpm
Enclosure class	IP68
Submersion	Max 250 m
Weight of motor and pump	18 kg

Table 4.
Electrical parameters of the pump motor.

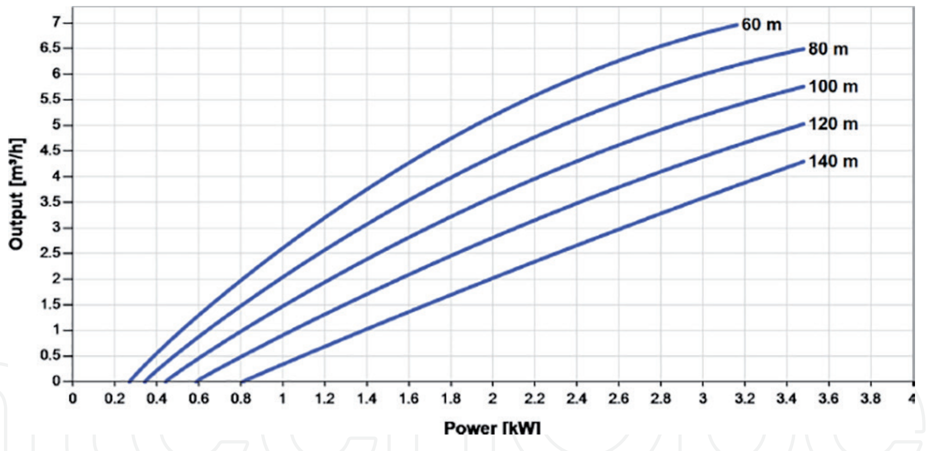

Figure 3.
Solar pump chart.

brushless DC motor, has no electronics in the motor. The electrical parameters of the pump motor are given in **Table 4**, while **Figure 3** illustrates the pump chart.

3. Optimization of hybrid PV/WT pumping system

To reach optimum system configurations, alternative configurations supplying the estimated daily load pattern are used to simulate the system performance. The optimum system fulfills the load requirements within the acceptable percentage of unmet load which is one of the decision variables. Optimality condition is based on the objective minimum cost which is defined by two criteria; the first is the minimum net present cost (NPC) and the second is the cost of energy (COE) generated from the system.

3.1 Hourly load curve estimation

The daily quantity of water required for irrigation is about 50 m^3 in summer and 42 m^3 in winter. Water is pumped for 7 hours on average. Thus, the hourly pumped quantity is 7 m^3/hour for summer and 6 m^3/hour for winter. The submersed pump is installed at a distance 41 m from ground level, assuming that the tank is at 2 m above the ground, and then the total elevating head is 43 m. Then the electrical power required for water pumping for summer is about 1.5 kW and for winter 1.3 kW. The estimated hourly electrical load is shown in **Table 5**.

Time (hour)	Winter		Summer	
	Q (M^3/hour)	kW	Q (M^3/hour)	kW
10	3	0.65	3	0.65
11	6	1.3	7	1.5
12	8	1.7	10	2.14
13	8	1.7	10	2.14
14	8	1.7	10	2.14
15	6	1.3	7	1.5
16	3	0.65	3	0.65

Table 5.
Hourly electric load of water pumping system.

For economic comparison purposes of the hybrid PV/WT pumping systems, five cases of the different investigated system configurations are simulated and analyzed using software packages PVSYST and HOMER. The proposed systems are as follows: (i) PV system, (ii) PV/HAWT), (iii) PV/VAWT, (iv) PV/VAWT/D and (v) diesel only system. The simulation is also carried out for different load patterns.

4. Results and discussion

4.1 Case 1: PV only

In this case, the system used the PV arrays only to drive the pump via a converter. Four batteries (12 V, 200 AH each) were included in the system simulation to control the energy shortage. The NPC and COE resulted from system simulation over 25 years are shown in **Table 6**.

From **Table 6**, the total NPC of the PV system is 22,523$ and COE is 0.614$/kWh. The capacity shortage is about 8% of the total load, although four batteries are included in the system simulation. **Figures 4** and **5** illustrate the cash flow and energy flow summaries of PV pumping system.

The cash flow summary shows that the capital cost of the PV modules is 5000$ and the O&M costs over 25 years lifetime is 5337$, this means that the total PV costs over the simulation period is 10,337$. The batteries capital 1800$, replacement cost over system lifetime is 4903$ and batteries O&M cost is 2135$. Hence the total batteries cost is 8711$. This means that batteries total cost is about 38.7% of system total NPC. The energy summary (**Figure 8**) shows that although 4.7% of the load is not supported (unmet load) about 31.6% of the generated electricity is wasted (excess energy).

4.2 Case 2: PV/HAWT

The second case used hybrid PV arrays with 1 kW horizontal axis wind turbine to drive the pumping system via controller in addition to the four batteries used in case 1. The simulation was carried out for two cases according to the life time of the PV array (25 years) and lifetime of the wind turbine (15 years). The power curve of the used wind turbine is shown in **Figure 9**. It is clear that the monthly average wind speed on site are 5.53 m/second (**Table 1**) which is much lower than the turbine rated wind speed about 10 m/second (**Figure 6**), which is greatly affect to the performance of the used wind turbine and hence overall system economics.

Tables 7 and **8** show the simulation results of the PV/HAWT pumping system over 25 and 15 years, respectively. It is clear that the NPC of the system are 31,988 and 25,019$ while the COE are 0.855 and 0.834$/kWh for both cases, which are higher than case of PV only (**Table 6**). In other words, the PV system is more economic than PV/HAWT, due to the lower values of the monthly average wind speed on site than the turbine rated wind speed.

			PV (kW)	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
			3.3	4	5	CC	$ 8,300	1,332	$ 22,523	0.614	1.00	0.08
			3.3	4	5	LF	$ 8,300	1,332	$ 22,523	0.614	1.00	0.08

Table 6.
NPC and COE of PV system for water pumping.

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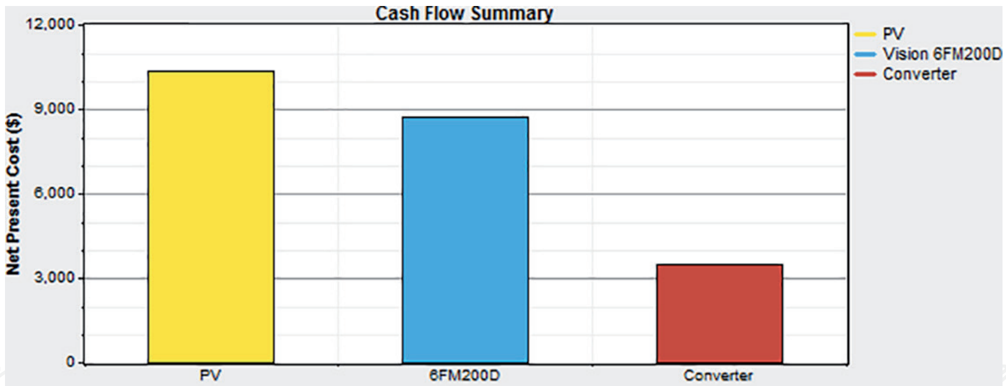


Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	5,000	0	5,337	0	0	10,337
Vision 6FM200D	1,800	4,903	2,135	0	-127	8,711
Converter	1,500	1,017	1,067	0	-110	3,475
System	8,300	5,920	8,540	0	-237	22,523

Figure 4.
Cash flow summary of PV pumping system.

Production	kWh/yr	%
PV array	5,978	100
Total	5,978	100

Consumption	kWh/yr	%
AC primary load	3,434	100
Total	3,434	100

Quantity	kWh/yr	%
Excess electricity	1,892	31.6
Unmet electric load	168	4.7
Capacity shortage	297	8.3

Quantity	Value
Renewable fraction	1.00
Max. renew. penetration	1,110 %

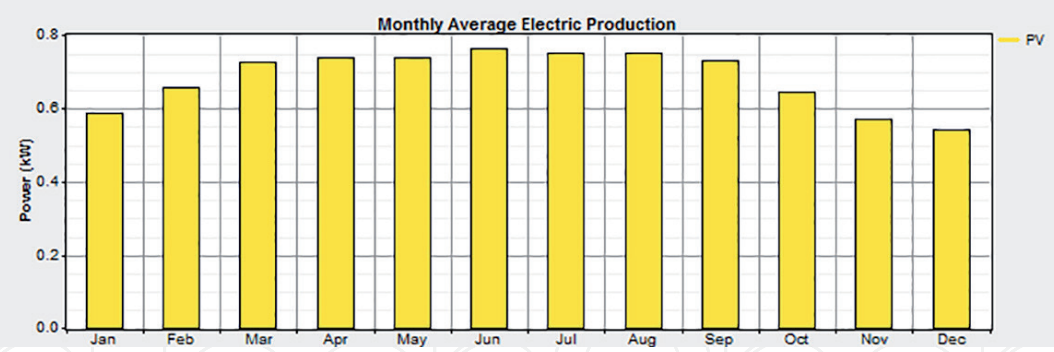


Figure 5.
Energy summary of PV pumping system.

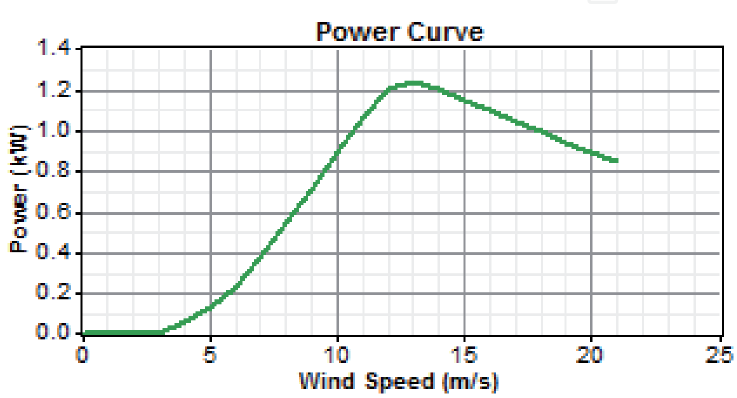
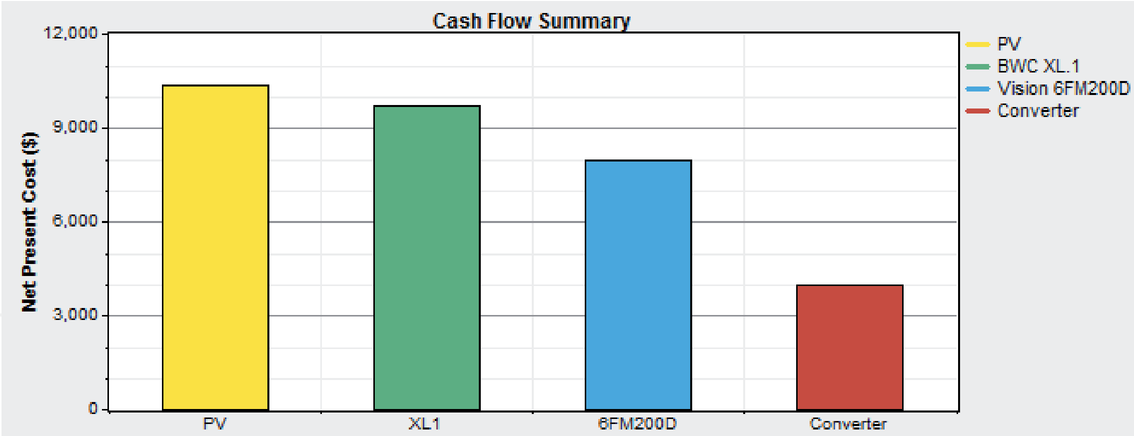
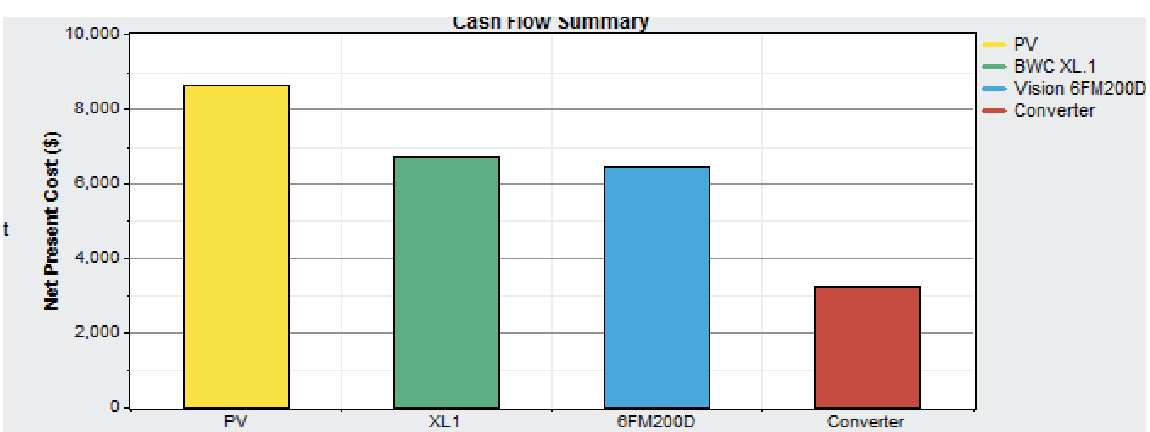


Figure 6.
Wind turbine power curve.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	5,000	0	5,337	0	0	10,337
BWC XL.1	6,000	1,891	2,135	0	-292	9,734
Vision 6FM200D	1,800	4,182	2,135	0	-156	7,960
Converter	1,800	1,220	1,067	0	-131	3,956
System	14,600	7,293	10,675	0	-580	31,988

Figure 7.
Cash flow summary of PV/HAWT pumping system (25 years).



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	5,000	0	4,280	0	-630	8,649
BWC XL.1	5,000	0	1,712	0	0	6,712
Vision 6FM200D	1,800	3,237	1,712	0	-297	6,452
Converter	1,800	834	856	0	-284	3,206
System	13,600	4,071	8,559	0	-1,211	25,019

Figure 8.
Cash flow summary of PV/HAWT pumping system (15 years).

Figures 7 and **8** present the cash flow summary of the system simulation over 25 and 15 years while **Figure 9** illustrates the PV/HAWT system energy summary (25 years). It is clear that the operation of 15 years only saves the replacement of the wind turbine and reduces the system O&M costs. **Figure 9** shows that about 44.2% of the generated electricity is not used (excess energy) which may explain the increase in the COE while only 3.9% of capacity shortage of the load is not supported, which is less than that of PV system only (8.3%, **Figure 5**).

4.3 Case 3: PV/VAWT

For comparison between horizontal and vertical axis wind turbines, case 3 represented the water pumping system derived by PV arrays with vertical axis wind

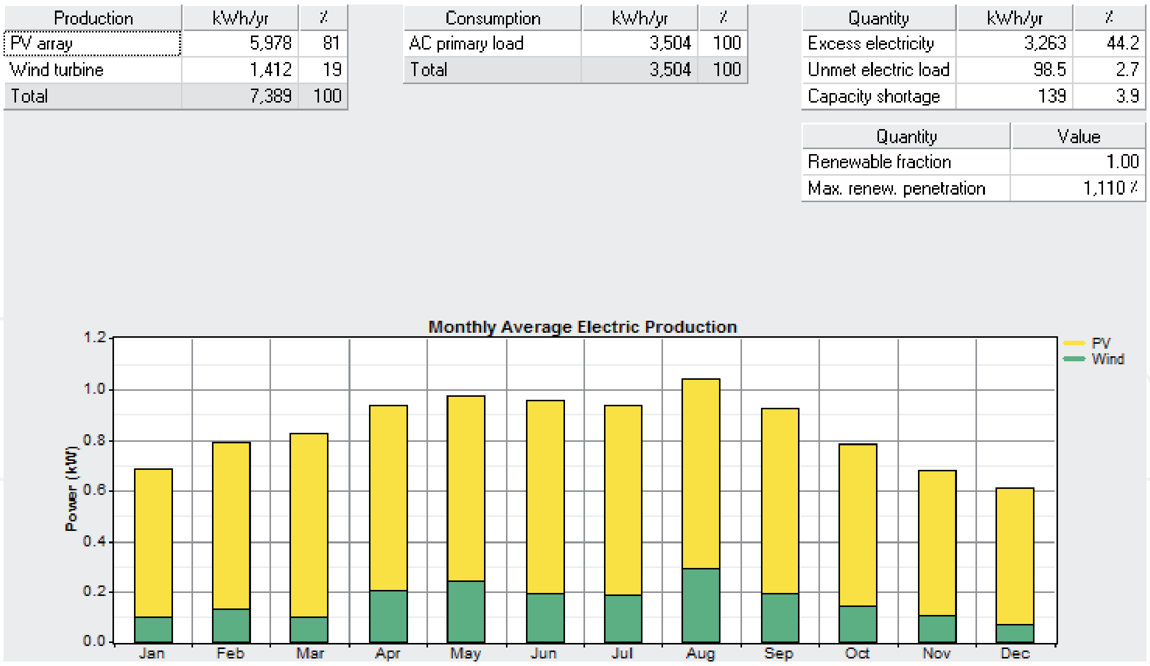


Figure 9.
Energy summary of PV/HAWT pumping system.

PV (kW)	XL1	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
3.3		4	5	CC	$ 8,600	1,349	$ 23,004	0.627	1.00	0.06
3.3		4	5	LF	$ 8,600	1,349	$ 23,004	0.627	1.00	0.06
3.3	1	4	5	CC	$ 14,600	1,629	$ 31,988	0.855	1.00	0.04
3.3	1	4	5	LF	$ 14,600	1,629	$ 31,988	0.855	1.00	0.04

Table 7.
Optimization results of hybrid PV/HAWT pumping system (25 years).

PV (kW)	XL1	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
3.3		4	5	CC	$ 8,600	1,203	$ 18,897	0.643	1.00	0.06
3.3		4	5	LF	$ 8,600	1,203	$ 18,897	0.643	1.00	0.06
3.3	1	4	5	CC	$ 13,600	1,334	$ 25,019	0.834	1.00	0.04
3.3	1	4	5	LF	$ 13,600	1,334	$ 25,019	0.834	1.00	0.04

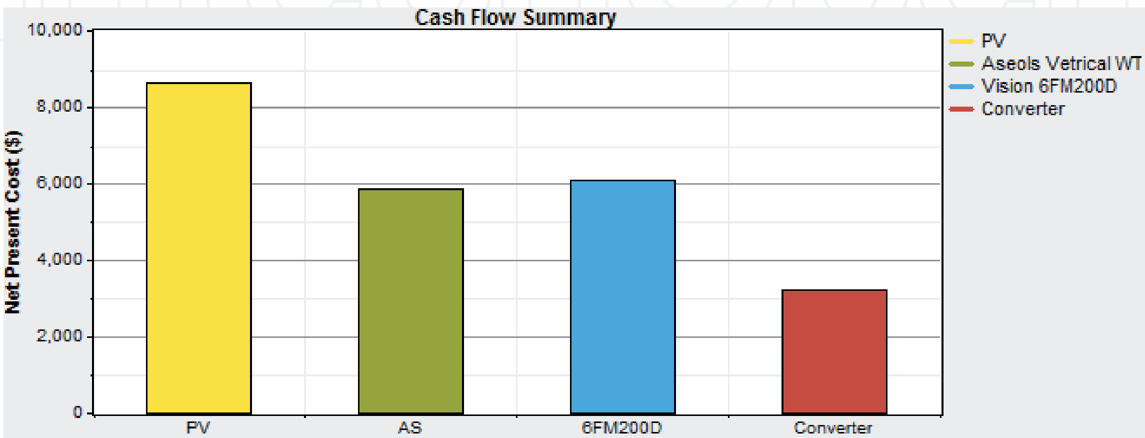
Table 8.
Optimization results of hybrid PV/HAWT pumping system (15 years).

PV (kW)	AS	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
3.3		4	5	CC	$ 8,600	1,203	$ 18,897	0.643	1.00	0.06
3.3		4	5	LF	$ 8,600	1,203	$ 18,897	0.643	1.00	0.06
3.3	1	4	5	CC	$ 13,600	1,195	$ 23,825	0.790	1.00	0.03
3.3	1	4	5	LF	$ 13,600	1,195	$ 23,825	0.790	1.00	0.03

Table 9.
Optimization results of PV/VAWT pumping system.

turbine via pump converter with the pre-described storage batteries. The system was simulated for 15 years. **Table 9** exhibits the optimization results of system and **Figures 10** and **11** present the system cash flow summary and energy summary, respectively.

Table 9 shows that the NPC of PV/VAWT is 23,285$ and the COE is 0.790$/kWh. The energy summary (**Figure 11**) shows that the excess energy recorded in this case is about 49.6% (compared to 31.6% in case of PV system and 44.2% in case of PV/HAWT). In fact, the amount of increase in excess energy is almost equal to the energy generated from the wind turbine. Hence it is recommended to use this abandoned energy in elevating more water that could be used for irrigation or domestic use. In this case the COE generated from the PV/VAWT will be reduced. From **Figures 9** and **11**, it is clear that the capacity shortages are almost equals for both types of wind turbines (PV/HAWT, 3.9 and PV/VAWT, 3.1).



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	5,000	0	4,280	0	-630	8,649
Aseols Vetrical WT	5,000	0	856	0	0	5,856
Vision 6FM200D	1,800	3,072	1,712	0	-471	6,113
Converter	1,800	834	856	0	-284	3,206
System	13,600	3,906	7,704	0	-1,385	23,825

Figure 10.
Cash flow summary of PV/VAWT pumping system.

Production	kWh/yr	%
PV array	5,978	73
Wind turbine	2,209	27
Total	8,186	100

Consumption	kWh/yr	%
AC primary load	3,523	100
Total	3,523	100

Quantity	kWh/yr	%
Excess electricity	4,057	49.6
Unmet electric load	79.1	2.2
Capacity shortage	113	3.1

Quantity	Value
Renewable fraction	1.00
Max. renew. penetration	1,130 %

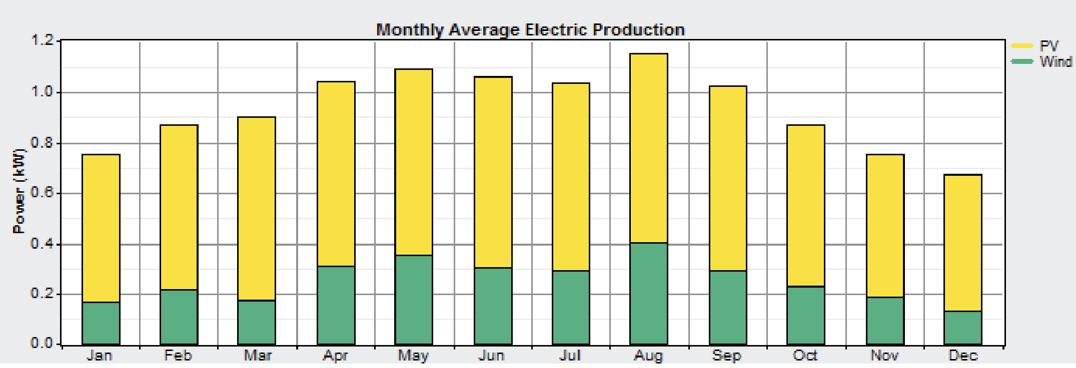


Figure 11.
Energy summary of PV/VAWT pumping system.

4.4 Case 4: PV/HAWT/diesel

Case 4 represents a PV array with HAWT with diesel generator to supply the required electrical energy for the water pumping system with the required pump converter with batteries. **Table 10** shows the simulation results of the proposed system for 15 years, while **Figures 12** and **13** present the system cash flow summary and energy summary.

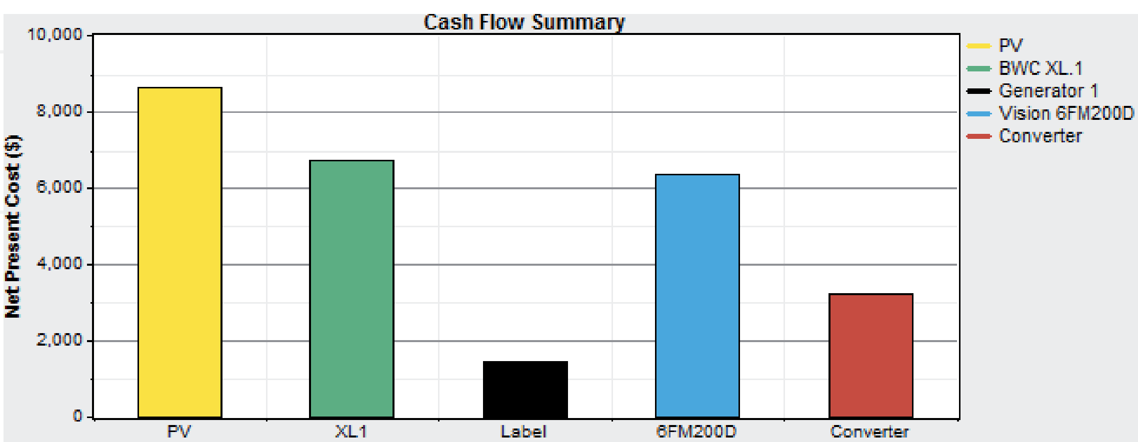
Table 10 showed that the NPC for PV/HAWT/diesel system is 26,383$ and COE is 0.857$/kWh, which is slightly more than that of PV/VAWT or PV/HAWT and higher than that of PV system only (0.643$/kWh). The energy summary (**Figure 16**) also shows that the excess energy is about 43.9% of the generated electricity; hence the same recommendation of energy management applies. The great advantage of this system configuration is the smallest capacity shortage (0.4%).

4.5 Case 5: diesel alone

For the sake of comparison, it was assumed that the required electrical energy for water pumping is supplied by a diesel generator only. The length of the simulation run is 15 years. **Table 11** presents the NPC and COE based on fuel price of 0.4$/L. In fact, this case will differ as the price is expected to rise. Also, the external

PV (kW)	XL1	Label (kW)	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
3.3			4	5	CC	$ 8,600	1,203	$ 18,897	0.643	1.00	0.06		
3.3			4	5	LF	$ 8,600	1,203	$ 18,897	0.643	1.00	0.06		
3.3		1	4	5	LF	$ 9,100	1,381	$ 20,920	0.681	0.95	0.01	60	199
3.3		1	4	5	CC	$ 9,100	1,763	$ 24,192	0.786	0.85	0.00	174	527
3.3	1		4	5	CC	$ 13,600	1,334	$ 25,019	0.834	1.00	0.04		
3.3	1		4	5	LF	$ 13,600	1,334	$ 25,019	0.834	1.00	0.04		
3.3	1	1	4	5	LF	$ 14,100	1,435	$ 26,383	0.857	0.97	0.00	38	130
3.3	1	1	4	5	CC	$ 14,100	1,701	$ 28,658	0.930	0.90	0.00	119	361

Table 10.
Optimization results of PV/VAWT/diesel pumping system.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	5,000	0	4,280	0	-630	8,649
BWC XL.1	5,000	0	1,712	0	0	6,712
Generator 1	500	277	556	132	-8	1,457
Vision 6FM200D	1,800	3,193	1,712	0	-345	6,360
Converter	1,800	834	856	0	-284	3,206
System	14,100	4,304	9,116	132	-1,268	26,383

Figure 12.
Cash flow summary of PV/HAWT/diesel pumping system.

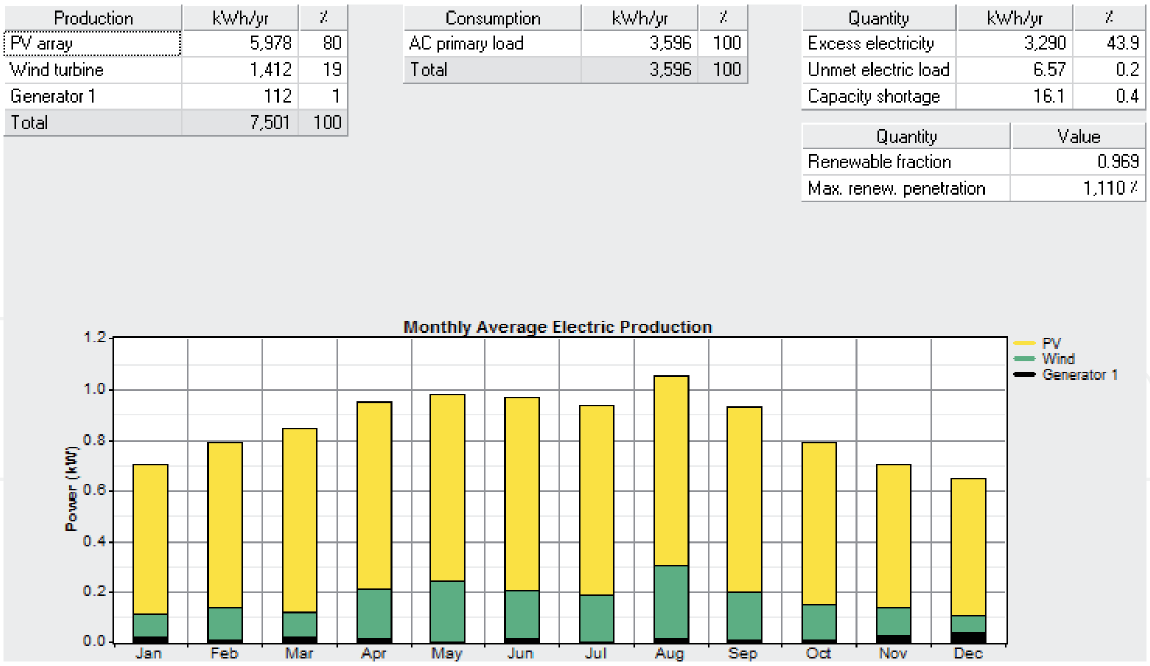


Figure 13.
Energy summary of PV/HAWT/diesel pumping system.

	Label (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)	Label (hrs)
	4	CC	$ 2,000	2,924	$ 27,026	0.876	0.00	0.00	1,836	2,555

Table 11.
Optimization results of diesel water pumping system.

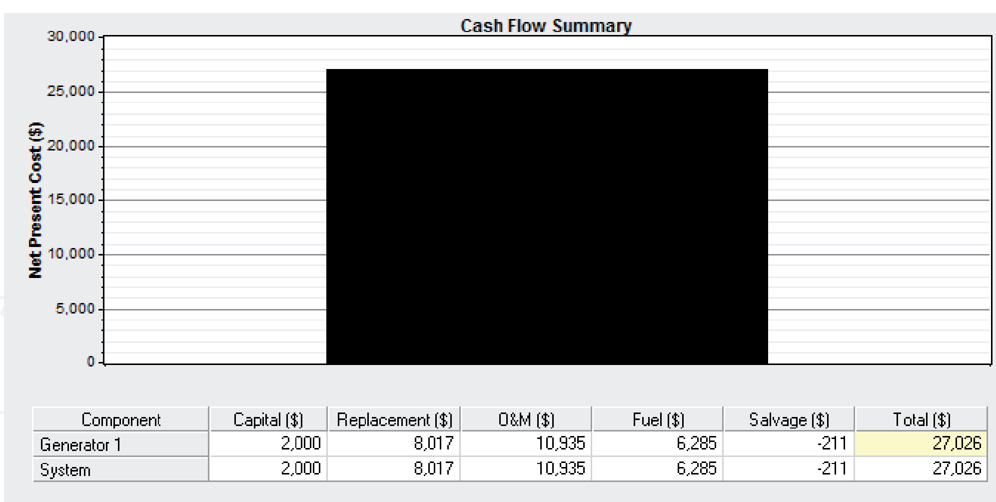


Figure 14.
Cash flow summary of diesel pumping system.

cost (cost of CO_2 emissions) is not taken into consideration. Thus, the COE should be higher than the simulated values. **Figures 14** and **15** present the system cash flow summary and energy summary.

The total NPC of the diesel system is 27,026$ which is considered the highest NPC of all previous systems. Comparing the COE in **Table 11** by COE generated by PV system and PV/WT systems (**Tables 6–10**), it is clear that the cost of electricity generated from diesel generator ($0.876, **Table 11**) is higher than PV alone ($0.643, **Table 9**) or PV/VAWT system ($0.79, **Table 9**). **Figure 15** shows that although the diesel system has the highest NPC, the system satisfies zero shortage capacity.

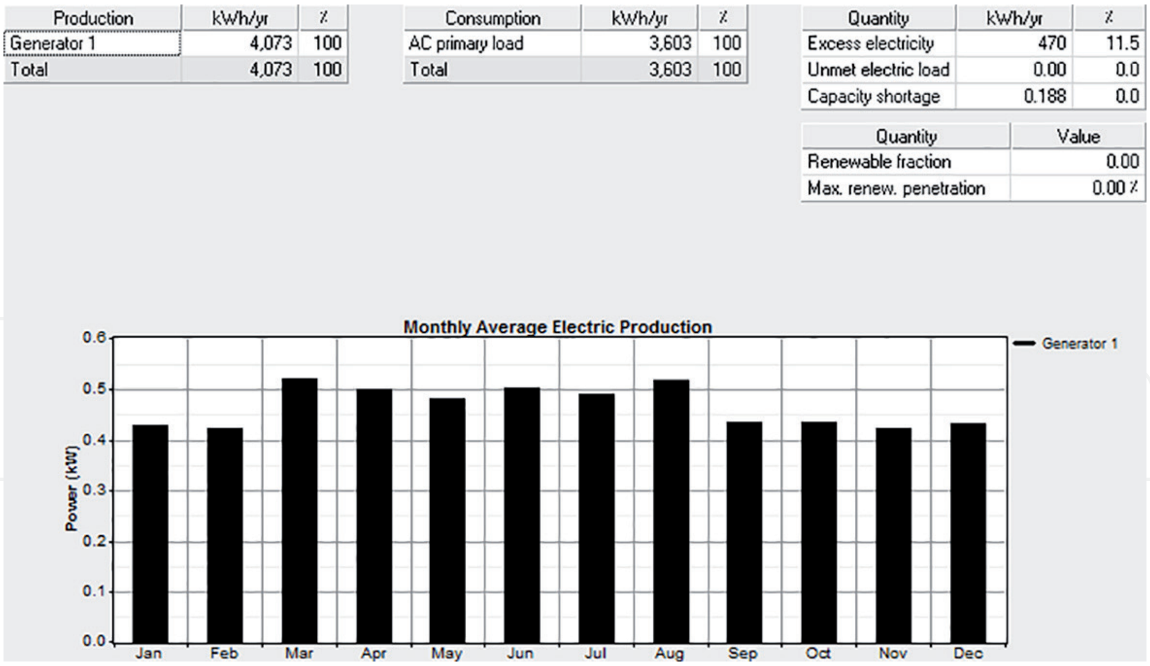


Figure 15.
Energy summary of diesel pumping system.

Time (hour)	Winter		Summer	
	Q (M^3/hour)	kW	Q (M^3/hour)	kW
7	3	0.65	3	0.65
8	3	0.65	4	0.86
9	3	0.65	4	0.86
10	6	1.3	4	0.86
11	7	1.5	7	1.5
12	8	1.7	10	2.14
13	8	1.7	10	2.14
14	8	1.7	10	2.14
15	6	1.3	7	1.5
16	3	0.65	4	0.86
17	0	0	3	0.65

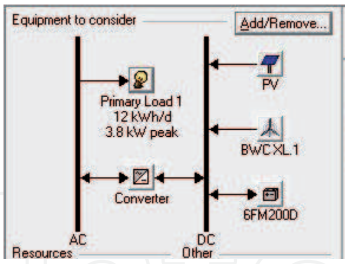
Table 12.
New load pattern.

4.6 Case 6: PV/HAWT for modified load pattern

As it is clear from the above applied PV/WT systems, the excess energy represents a large amount of generated electricity that reached about 50% in one of the cases (PV/VAWT). This should be handled through applying a load management policy. Hence the load pattern is modified and increased by 3.24 kWh/day distributed over 6 hours per day. The new load profile is presented in **Table 12** while the results of this run are illustrated in **Table 13** and **Figure 16**.

It could be seen in **Table 13** that COE is decreased from 0.834$/kWh (**Table 8**) to 0.758$/kWh, NPC is 25,984. **Table 13** shows that the peak load is 12 kWh/day; with peak of 3.8 kW. The excess energy decreased to 35.8% (was 44.2%) which is the cause of the decreased COE. Increasing the load another time by 0.1 kW the

COE will be 0.678$/kWh with NPC is 25,883$. **Figure 17** illustrates the relation between the daily load in kWh and the cost of energy in $/kWh.



Simulations: 32 of 32 Sensitivities: 1 of 1 Progress: Status: Completed in 1 seconds.

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	XL1	6FM200D	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
3.3		4	5	CC	$ 8,600	1,297	$ 19,705	0.598	1.00	0.13
3.3		4	5	LF	$ 8,600	1,297	$ 19,705	0.598	1.00	0.13
3.3	1	4	5	CC	$ 13,600	1,447	$ 25,984	0.758	1.00	0.09
3.3	1	4	5	LF	$ 13,600	1,447	$ 25,984	0.758	1.00	0.09

Table 13.
Optimization results of hybrid PV/VAWT pumping system for modified load pattern.

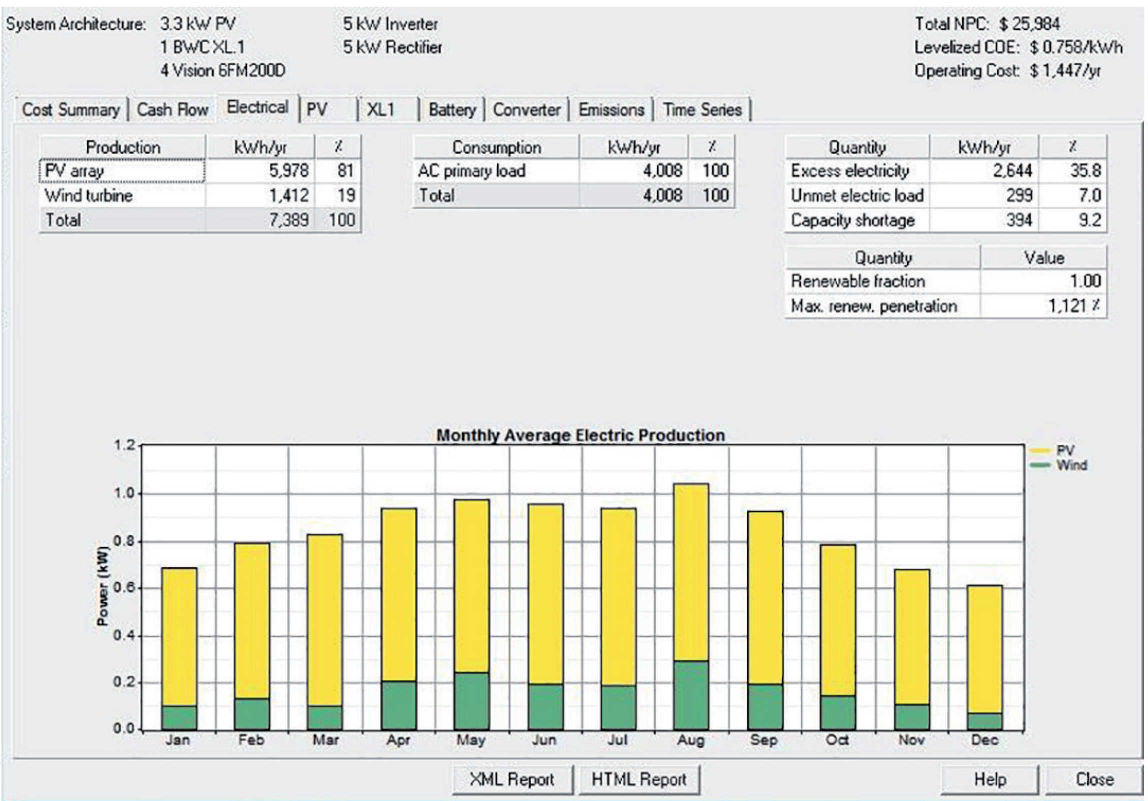


Figure 16.
Cash flow summary of PV/HAWT pumping system with modified load pattern.

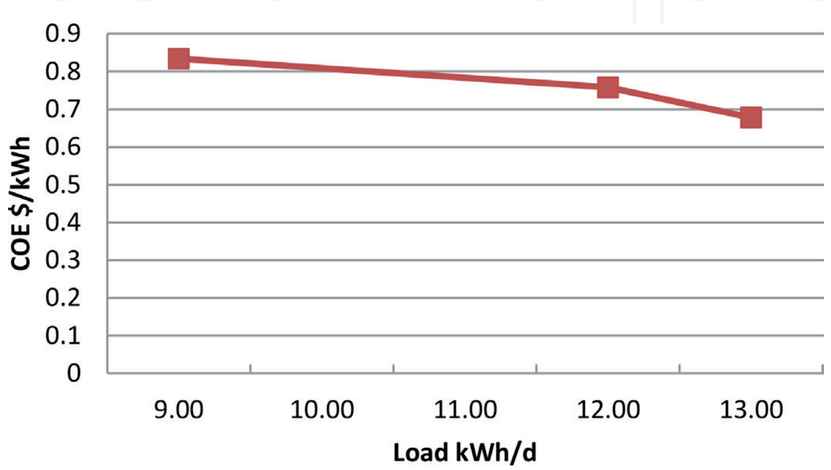


Figure 17.
Relation between daily load and cost of energy (COE).

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5. Conclusions

The present chapter illustrates the specifications of an installed PV water pumping system for agriculture purposes in El-Tour city, Sinai, Egypt. For economic comparison, the paper theoretically analyzed different renewable energy water pumping systems with different load patterns using commercial software. The systems using only PV power, PV/WT vertical and horizontal types with and without diesel generator. The systems contain storage batteries. The economic analysis was carried out based on the NPC and COE with system capacity shortage. The result of the analysis showed the following conclusions:

- The NPC and COE is lower in case of PV only and increased by using WT with PV system due to the lower wind speed rates in the specified location. The COE was 0.614$/kWh for PV only, 0.834$/kWh for PV/HAWT, 0.790$/kWh for PV/VAWT, 0.857$/kWh for PV/HAWT/diesel and 0.876$/kWh for diesel generator only. The external cost of CO_2 emissions is not taken into consideration which will raise the cost of energy generated from diesel alone system.

- The capacity shortage percent decreased with using diesel generator in the system, although the NPC increased. The capacity shortage was 8.3% for PV only, 3.9% for PV/HAWT, 3.1% for PV/VAWT, 0.4% for PV/HAWT/diesel and zero for diesel system only.

- Monthly average wind speeds on the location are much lower than the turbine rated wind speed which leads to non-optimal operation of the PV/WT. This leads to higher NPC and COE values. Also, high percentage of excess energy is noticed in cases of PV/WT system which causes the increase of COE.

- Increasing the load during the periods of excess energy decreases the COE. Thus, it is recommended to use abandoned energy in other optional loads.

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