

Analysis of an Off-Grid Photovoltaic-Wind Hybrid Power System for Disi Water Pumping Project

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Abstract

A standalone hybrid PV/ wind energy system is proposed to be used to continuously power a submersible water pump from a selected well out of 55 production wells located at the Disi aquifer, South of Jordan. Each of these wells has a continuously-operating water flow rate of 288 m³/h. Excess energy, if any, is to be stored in the form of a pumped water storage at the ground level near the well. Solar radiation and wind speed data for Al-Mudawara border meteorological station, which was taken as a representative of the Disi water aquifer were collected and analyzed. Energy analysis was monthly made on the basis of average daily available energy. The performance of three PV/wind power plant scenarios was analyzed through the study of the underground water pumping wells using Life Cycle Cost (LCC) method. It was found that, for one scenario, the hybridization of a 16.5 MW is produced by PV power plant and 27.5 MW by wind power plant at Al-Mudawara site is the optimal scenario which is economically and technically feasible. It was found that the storage energy covered the load after implementation of the proposed project, the cost of 1 kWh of energy produced was estimated to be 0.16 \$/kWh., and the system payback period was 4.5 years.

Keywords: *Hybrid system, Off- Grid, Storage tank.*

1. Introduction

Disi is a water aquifer stretching from the Southern edge of the Dead Sea in Jordan to Tabuk in Northwest borders of Saudi Arabia. Figure 1 shows the topographical map of Jordan, where Al-Mudawara is at its Southern tip.

Significant exploitation of the Jordanian side of the aquifer with a stable upper layer and scattered scabs started in 1980. At present, Aqaba city is supplied with 16.5 MCM for domestic purposes and 75 MCM for agricultural purposes. Saudi Arabia develops around 4 BCM yearly and uses it for irrigation purposes. The wind turbine was installed at one of the water wells in the Disi aquifer, at the Jordan-Saudi Arabia border, as a replacement for a diesel engine driven vertical shaft pump [1]. The pump has been operated since then, with only minor maintenance routines and is extracting a sufficient quantity of drinking water to the border check point and the local Bedouins.

A PV-Wind hybrid system was proposed to produce enough energy to drive existing pumping systems in the Disi. In addition, extra energy will be used to store pumped water at ground level at the same location. One typical water well at power demand of 250 kW was selected to be provided with the required energy in this work. Qandil [2] designed an off-grid PV system that supplies required energy for Disi water pumping from that field to Amman. He assumed a continuous flow of 80 Liter/s per well, and found that the power required for the system was about 13.75 MW. Matthias [3] evaluated the financial feasibility of PV-Wind hybrid system installed in Germany. He found that the decentralized pumped storage hydropower plants remained the most efficient option to store electricity surplus from intermittent sources. The pumped storage plant can adapt the frequency of the grid when the load changes within a short period of time. Dhrab et al [4] were the first to discuss the feasibility of using hybrid PV-Wind system in Jordan. They discussed providing four cities with electrical energy but their system was grid connected and did not contain any storage features. They indicated that the location can be affected by the output energy of the wind turbine. Abu-Aligah [5] made a comparison between photovoltaic water pumping

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and diesel powered pumping. He found that the maintenance and life-time running cost of a PV system are negligible compared to those of the conventional energy systems such as diesel. The initial cost of a PV system is significantly higher but the operation cost is much lower.

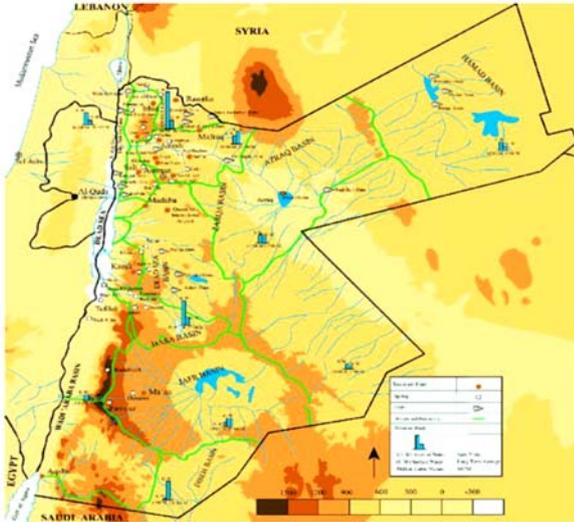


Figure 1. Jordan's topographical map

Ismail et al [6] proposed a case study of optimizing different types of hybrid systems (PV-Wind, wind-diesel, Storage Battery and Diesel Generator) to supply a load in Nablus and Ramallah sites in Palestine. They found that the best solution to choose the appropriate size of various components for the most optimum scenario is based on the cost of generation. They also found that the PV-Wind, diesel with storage battery hybrid system was the best scenario.

In this work, a hybrid system (PV and wind) was proposed for Disi water pumping project, located near Al-Muawara border post south of Jordan (latitude 29°12'N) as an appropriate system that utilizes renewable energy resources as well as energy storage features in Jordan. The system consists of 55 wells that consume about 44 MW. One typical well was selected which consumes 300 kW of PV power and 500 kW of wind turbine power.

2. Water in Jordan

In terms of water available to each citizen, Jordan is considered one of the driest ten countries in the world. Already scarce water resources will soon be even thinner, with the population predicted to double in less than 25 years. Jordan's thriving population drives the demand for water, but it additionally promotes unregulated development, which pollutes the groundwater on which people depend. Most of the increase in the area of irrigated land in the world was due to the increasing use of engine-driven pumps. However, the increasing price of oil-based fuel has reduced the margin gained by farmers from irrigation, since it was generally prevented to raise food prices in line with energy costs. Despite the present short-term fluctuations in oil prices, conventional oil-based engine-driven power sources and electricity mains are expected to keep on increasing in the long term. If Jordan chose to downgrade their dependence on imported oil, they will have to find methods for energizing irrigation pumps that are independent of imported oil or centralized electricity. Solar radiation as a source of energy is, of course, the symbol of the clean and sustainable

energy technology, except for residues, possibly arising from the manufacture of solar component (e.g semiconductors). Solar technology has very low environmental impacts. The environmental impacts of solar system in operation are very low and the source is, for us, renewable and inexhaustible. The Ministry of Water and Irrigation (MWI) is concerned looking at the potential options of generating renewable energy to serve reduce the cost of electricity that should cover the water sector. The aim of this study is to find the basic economic figures to make a decision for the future electricity supply for the water sector as well as to prepare for the related regulatory negotiations between the Ministry of Water & Irrigation and the National Electric Power Company (NEPCO), and the Jordan electric distribution companies. This study was conducted by a joint team of MWI, GIZ and Jordan Chamber of Industry (JCI). In the preparation sessions, the scope of the study was stretched to include wind turbine options. The study assumed an overall water use in Jordan of 1 Billion m³/year, while the annual consumption of electricity for water supply is 1939 GWh/y (2011) [7]. Thus the overall average specific electricity demand for water supply is 1.9 kWh/m³[7].

The electricity tariff for the water sector has been changed in 2013, where the fee for kWh is to increase annually, from 76 fils in 2013 to 133 fils in 2017, (\$1.0≈700fils) as shown in Table 1. Thus in 2017, the electricity bill for water supply in Jordan will rise to a total amount of 258 Million JD assuming the amount of water consumption is situated at 1 billion m³ (which is very unlikely)[7]. After 2017, one should assume an annual rise of at least 2% in the electricity tariff. The costs above do not include the power demand of the Disi Water Conveyance project; where it is estimated (based on the WAJ data for 2013) that each 1 m³ requires about 2.8 kWh, i.e. for 100 MCM the energy demand will be 280 GWh resulting in a cost of around 24 million JOD in 2014 [7]. These calculations make it imperative for MWI to consider renewable energy sources to decline the burden of electricity costs on the water sector. The study mainly considered solar energy generation potentials; it also includes wind energy where appropriate. Concentrated solar power is not further examined as it seems to be not economically viable under the current and conditions. The study offers an overall analysis i.e. with a vision to cover the total demand for electricity and also provides analysis for covering a modular approach [7].

Table 1. Tariff summary of electrical energy for water pumping plants and sewage treatment plants owned by Water Authority all over the Kingdom

Unit	15/8/2013 to 31/12/2013	2014	2015	2016	2017
Fils for each kWh sold	76	87	100	115	133

3. Renewable Energy Water Generation Based Scenario

Electrical power generation in Jordan depends predominantly on fossil fuels, which have significant impact on environment by emitting harmful greenhouse gases (GHG) such as CO₂ and NO_x. Power generation in 2013 achieved to around 17,261 Gwh, which corresponds to more than 15 million tons of CO₂

emissions. That is the real challenge is apparently added for the country. It advises switching to renewable energy and clean power generation systems to contribute to protect the local environment. If MWI is to consider a long term vision of generating all the electricity it consumes for water supply from alternative renewable resources, a total amount of about 1900 GWh/y has to be generated, assuming a supply of 1 billion m³. The investment for an overall renewable energy solution (combination of wind and photovoltaic) would be given an estimate of about 1.3 Billion JOD [12]. In order to finance this solution, the principal payments, the interest and the

maintenance cost would lead to yearly payments of about 150 million JOD per year over 20 years. As Figure 2 shows, the renewable energy system (RES) will be very attractive. The scenario of generating the entire consumption of electricity by renewable energy would yield in saving, in average, 144 million JOD per year for the life of the system (20 years) assuming an increase of 2% in tariff beyond 2017. If the tariff after 2017 stays constant at 133 fils/kWh, the savings will be around 100 million JOD per year over the total life span of the system.

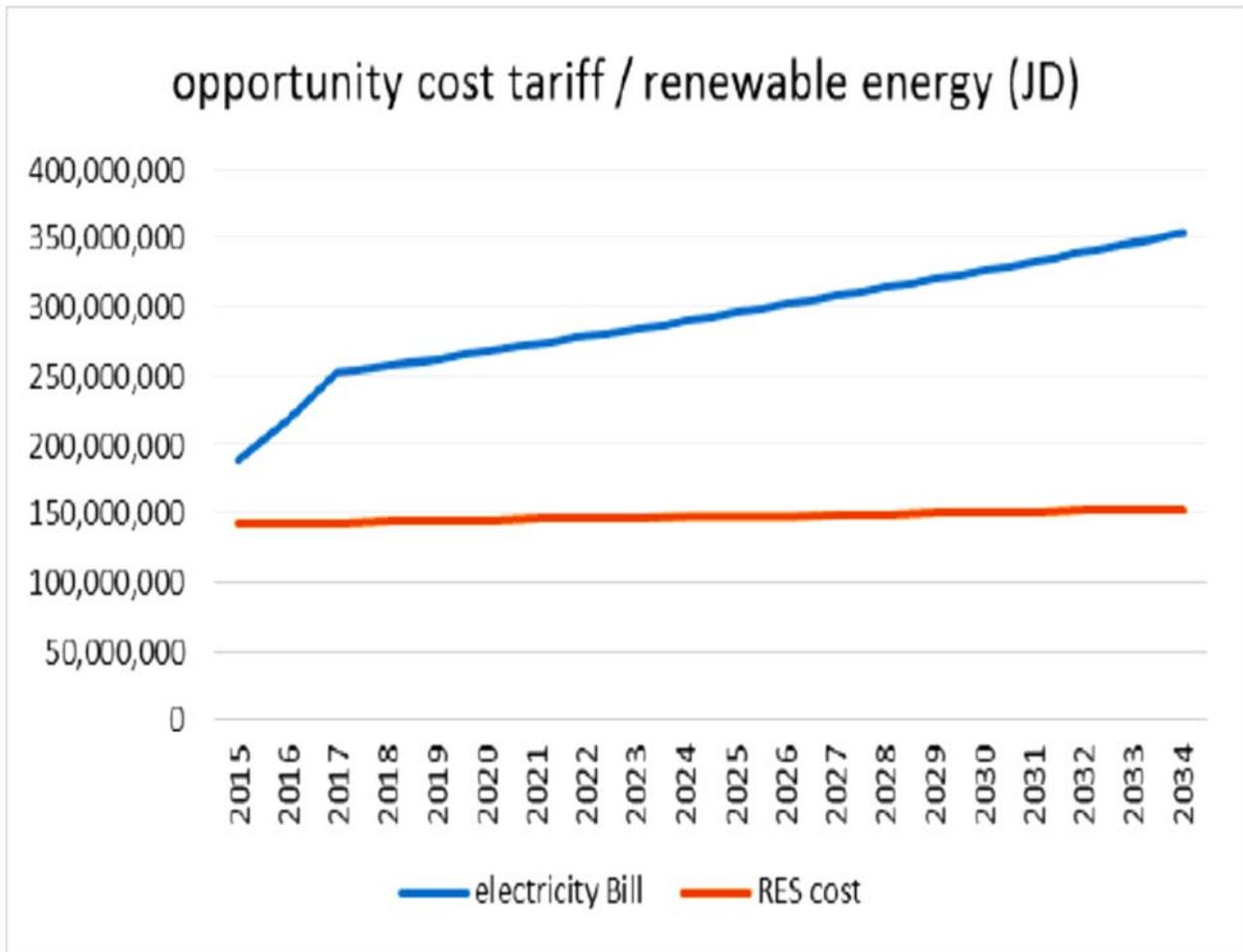


Figure 2. Comparison of conventional electricity consumption costs with renewables (wind and PV)

The above figures are based on the assumption of a decentralized solution for direct electricity consumption at the demand centers. That is installing a number of solar power generation plants where pumping stations and centers would cause additional costs.

4. Mathematical Model

4.1. PV module

A photovoltaic cell is a non-mechanical device usually made from silicon alloys. Photovoltaic cells, like batteries, generate direct current (DC) which is generally used for small loads (electronic equipment). The following equation calculates that

the number of module poly crystalline silicon cell type according to Duffie and Beckman [13] as:

$$\text{Number of modules} = \frac{A_c}{\text{module area}} \quad (1)$$

$$= 275,401$$

Where A_c is the land area and the module area is based on the poly crystalline silicon cell type that commercially is available and is at 1.64 m². Therefore, the crystalline silicon modules may be arranged in columns and rows, and those modules may be distributed over the total area of PV array in 19 columns and 8 rows for each well.

The total spacing between module rows can be evaluated according to eq. 2 as:

$$Y = 1'' + S = 4.68\text{m}$$

Where

$$S = h / \tan \alpha = 2.84\text{m}$$

The total spacing between module rows

$$Y = 1'' + S = 4.06\text{m}$$

Now, the land area considering the effect of shading on cell performance may be found as follows:

$$\text{Land area} = [(Y + \text{module thickness}) * \text{No. of rows}] * [\text{width of all module in each row}] \quad (2)$$

$$\text{Land area} = 234.11\text{m}^2$$

The area for offices, substations ...etc.centers would cause additional costs. If options for electricity or energy storage are to be included, this would necessitate further costs.

4.2. Inverter Selection

For selecting an appropriate inverter, three main factors should be taken into account; its output AC power, the dc-ac conversion efficiency and capital cost. Regarding the AC power output, the maximum electrical power needed by the submersible pump to elevate water from well was taken at the worst case condition. The second factor for inverter selection is the conversion efficiency from DC power to ac if the inverter is more efficient the battery bank will not be smaller (but the battery will not be used in this plant). To be considered the ac load matched to the suggested inverter and the inverters size in term of power output, is aimed at maximization efficiency level. Inverter manufacturers list the efficiencies of their units on all of their specification sheets, which usually contain two values, one is called the peak efficiency $\eta_{inv,p}$, and the other more reliable value is called the CEC weighted efficiency $\eta_{inv,CEC}$ (Published by the California Energy Commission). The capital cost of inverters, the third factor, differs widely due to the power size, efficiency, reliability and brand. Searching for the most suitable inverter brand requires taking in mind the basic demands of the required inverter. When sizing the inverter for a PV system, the actual power drawn from the PV array must be determined, the inverter power is equal to 33000 W with 97% efficiency.

4.3. Wind Turbine

The energy that can be converted by wind turbines to electrical energy is highly dependent on the local average wind speed.

The amount of power transferred to a wind turbine is directly proportional to the area swept out by the rotor, to the density of the air, and the cube of the wind speed and given by

$$P = 0.5\rho V^3 \quad (3)$$

The technical specification of the wind turbine used in the studied project are given in Table 2.

Table 2. Wind turbine specifications (Vestas V39, 500 kW)

Peak power (kW)	Swept area (m ²)	Rotor diameter (m)	Hub height (m)
500	1195	39	53

The availability factor, AF, is the amount of time that a power plant is able to produce electricity over a certain period of time divided by the amount of the total time available in that period. For wind turbines, the availability is calculated through deducting the time intervals that the speed of the wind is lower than cut-in or higher than cut-out speeds of the wind turbines.

$$AF = 1 - (n/N) \quad (4)$$

Where:

n : is the number of months when the wind speed is lower than the specified cut-in speed (<4.0 m/s)

N : is the total number of months.

$$AF = 1 - (125/300) = 58.33\%$$

Wind turbine efficiencies depend on many factors, especially its design, shape and other characteristics. Equation 4 is used to evaluate maximum theoretical wind turbine efficiency [14].

$$\eta_{max} = [1/4 \rho A (V_{in} + 1/3 V_{in}) (V_{in}^2 - (1/3 V_{in})^2)] / [1/2 \rho A V_{in}^3] \quad (5)$$

Where η_{max} is the maximum theoretical wind turbine efficiency, V_{in} is the entering wind speed, A is the swept area and ρ is the air density.

Hence

$$\eta_{max} = [1/4 \rho A (4/3 V_{in}) (8/9 V_{in}^2)] / [1/2 \rho A V_{in}^3] = 16/27 = 59.6\%$$

This means, it is no more extraction than 59.6% of available power in wind.

5. Metrological data

Al-Mudawara has annual global radiation of 2300 kWh/m², and annual average wind speed of 7.6 m/s. The real data for solar radiation and wind speed were measured at the Al-Mudawara site by National Energy Research Center at the Royal Scientific Society (nerc), per ten minute over one year, then a monthly average daily radiation and wind speed were computed. Table 3 shows the monthly average daily radiation and wind speed for Al-Mudawara.

Table 3. Monthly avg. daily solar and wind power of Al-Mudawara

Month	Daily radiation (kWh/m ² day)	Wind speed at height 53m (m/s)
January	4.204	6.94
February	5.089	8.62
March	6.235	8.56
April	6.939	8.01
May	7.735	8.00
June	8.537	9.15
July	8.287	8.76
August	7.752	8.72
September	6.860	8.01
October	5.265	6.29
November	4.485	6.51
December	3.786	6.31

The storage power can be calculated as follows:

$$\text{Storage power} = (\text{solar power} + \text{wind power}) - \text{load} \quad (6)$$

Figure 3 shows monthly daily solar, wind and storage power of Al-Mudawara

6. Storage Tank

The required tank to store the pumping water for four hours is sized with capacity of 5000 m³. The storage tank dimensions is 24 m diameter and 12 m height. It is made of steel (Al-Nazir) [15]. In this paper, the required pumping power is supplied by the storage energy of hybrid system to store in the tank. The total pumping water capacity was calculated as the following (Sahin et al) [16]:

$$Q t = P t / H \rho g \quad (7)$$

Where:

P: is the pumping water power which is supplied by the storage energy of hybrid system (W).

t: is the given period time (hour).

ρ : is the density of water (1000 kg/m³).

G: is the gravitational acceleration (9.8 m/s²).

H: is the total head (m).

Q: is the volumetric flow rate of water (m³/s).

$$Q t = 9800 \times 10^6 / 200 \times 1000 \times 9.8 = 5000 \text{m}^3$$

7. Results and Discussion

Economical analysis is given for the proposed hybrid system. Three scenarios are estimated for the cost of the plant, the first of which is that the plant is at full operating capacity by wind power plant, i.e. the system produce 27.5 MW capacity. The second would be that the plant is at full operating capacity by PV power plant, i.e. the system produce 22 MW capacity. The final scenario would be that both systems would share 44 MW, i.e. 27.5 MW produced by wind power plant and 16.5 MW by PV power plant. For each scenario, the Life Cycle Cost (LCC) method was used in order to find the payback period for the proposed system. Life Cycle Cost (LCC) is the total cost of purchase and operation of a project over its entire service life. Total cost includes the costs of acquisition, operation, maintenance and disposal. (Capehart et al 2006).

The LCC method here uses the Present Worth Value (P), which permits a comparing alternatives with different cash flows taking place at different times. For purposes of

conducting an economical analysis, Future worth (F) must be calculated taking into consideration the P. A sum of money has to be changed over from its value in one time period to its equivalent value in another time period which is the time of payback period. The formulas and compounded interest rates are assumed to be compounded annually, while cash flows are assumed to be at the end of the year. The PWV of total costs for each alternative is calculated, and the alternative scenario with the lowest LCC will be selected. Accordingly, a payback period for each scenario is predicted. The benefit/cost ratio is then calculated, thus, determining the feasibility of the scenario. This work follows the outlined economical analysis procedure and is presented.

In order to find F, the final worth of principal given that P is known:

$$F = P (1 + i)^n \quad (8)$$

Where:

i: is the annual interest rate or discount rate, and now it is assumed to be 9%; this may also be referred to as the minimum attractive rate of return or MARR).

n: is the number of annual interest periods, usually in years, and for this project it is 20 years.

P: is the present value (or present worth).

To find A, given that F is known

$$A = F [i / ((1 + i)^n - 1)] \quad (9)$$

A: is a single payment from series of n equal annual payments that is required for the investment to break even after n years.

F: is the future value (or future worth)

After n years period of time, this work should reach point of breakeven where all costs spent is returned back to the investor. To find breakeven period knowing that the future value of initial investment equals the future value of periodic saving, we use the following equation written in the form below:

$$F(1 + i)^{-n} = A[(1 + i)^n - 1 / i] \quad (10)$$

The Benefit/Cost Ratio, This ratio calculates the present worth of all benefits, calculates the present worth of all costs, and then takes the ratio of the two amounts.

$$B/C = \text{Equivalent Benefits} / \text{Equivalent costs} \quad (11)$$

Since the ratio came to be greater than 1, the project is economically feasible.

Figure 4 and Table 4 illustrate the comparison between all scenarios.

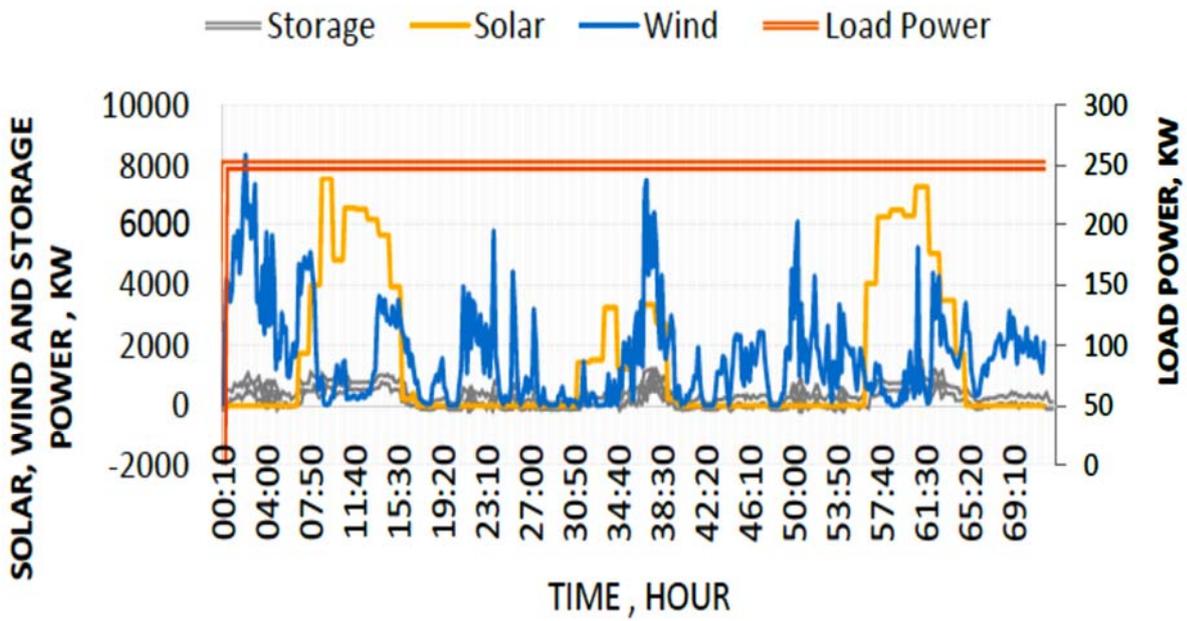


Figure 3. Monthly avg. daily solar, wind and storage power of Al-Mudawara

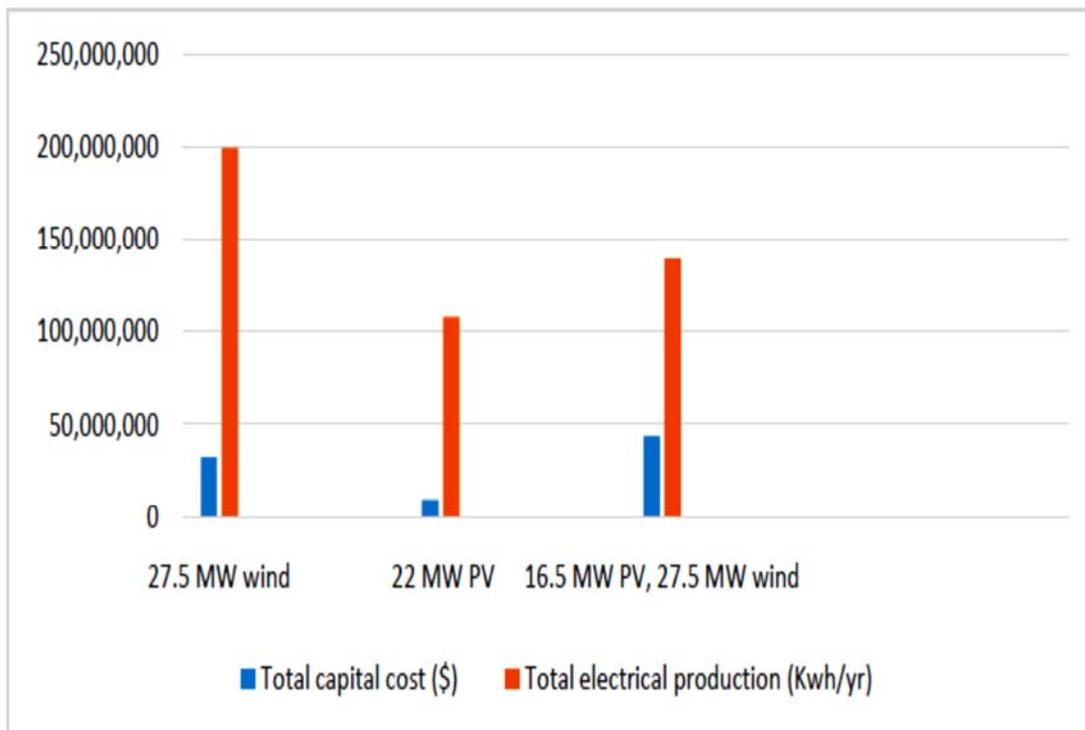


Figure 4. Comparison between all scenarios

Table 4. Comparison between all Scenarios

Type of power plant	Total capital cost (\$)	COE (\$/kWh)	Wind production (kWh/yr)	PV production (kWh/yr)	Break-even period (yr)	Benefit/Cost Ratio	Total electrical production (kWh/yr)
27.5 MW wind	32,768,950	0.3	110,547,376	-	4.6	2.5	110,547,376
22 MW PV	9,648,671	0.206	-	46,794,560	6	2	46,794,560
16.5 MW PV, 27.5 MW wind	44,171,644	0.085	110,547,376	35,095,536	4.5	4	145,642,882

The yearly amount of electrical energy generated from a 16.5 MW PV/ 27.5 MW wind plant at the site was estimated to be about 145,642,882kWh. That is possible to couple photovoltaic and wind together to produce a large-scale of electric energy in rare area and reduce the imports of energy needed to cover energy demand in Jordan.

8. Conclusion

In this article, a hybrid system comprising solar energy and wind energy, namely PV modules and wind turbine is proposed in Disi (Al-Mudawara) in Jordan to be one of the renewable based future systems in Jordan. The proposed system is off-grid connected system able to feed the water pumping system with the electric power requirement. The hybrid system compose of 300kW PV modules and 500 wind turbines for each well. The results shows that the power output from Al-Mudawara (which is part of Disi water well project) was found to have a high potential of solar and wind energy. From this study it can be concluded that the choice of the plant location can strongly affect the plant performance. Polycrystalline silicon modules, suited on a tilt angle of 29.1° rack structure was the suggested system configuration for the site in Al-Mudawara due to its promising incident solar radiation characteristics, which was resulting the huge energy from solar radiation around the year. It was also found that a steel storage tank of 5000 m³ capacity was capable of storing water pumped from the well at the ground level and the pay pack period was found about 6.2 years which is feasible for this investment and the benefit to cost ratio was about 1.6.

Nomenclature

D	Diameter of the turbine's rotor , m
A _c	Land area ,m ²
GIZ	Deutsche Gesellschaft fuer Internationale Zusammenarbeit

Greek Symbols

A_s Angle made by the projection of a direct solar beam and southern direction, °

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