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An optimized off-grid hybrid system for power generation in rural areas

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ABSTRACT

Stand-alone hybrid power generation system for a cow farm in Jordan is economically and technically optimized to meet the daily electrical load of the farm. A combination of photovoltaics, biogas generators, diesel generators, wind turbines, and batteries are used to determine the best scenario for the farm's power generation. In accordance with the price and technical data of the components, the systems were first studied technically and economically, and then simulated using hybrid optimization model for multiple energy resources (HOMER) software to identify the best configuration. Several options were analyzed to determine the best configuration. The optimized hybrid system includes photovoltaics, a biogas generator, batteries, and a diesel generator. The optimum configuration had a levelized cost of energy of $0.06 per kWh and a net present cost of $2,100,000. The renewable fraction of the total system electrical yearly production was 94%. Furthermore, the results showed that the optimized hybrid system could reduce the emitted gasses by about 92%.

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1. INTRODUCTION

Communities depend on energy for their development. For remote communities without easy access to the main power grid, stand-alone power generation has become an attractive option [1]. As a result of limited fossil fuel reserves and negative side effects of conventional power sources, scientists are seeking more sustainable energy technologies [2]. Researchers investigated innovative ideas to reduce reliance on fossil fuels by proposing self-contained demonstration units powered by solar, wind, biomass, and, minimized to the extent possible, fossil fuels [3]. Even though renewable energy sources are considered an alternative to fossil fuel, they aren't able to meet the load delivered due to their sessional and temporal variations [4]. So hybrid energy systems are among the most efficient systems that can be installed in remote areas [5]-[7]. Researchers have been studying the integration of conventional fuel combustion engines and renewable sources of energy including solar panels and/or wind turbines for the past two decades [8], [9]. Díaz *et al*. [10] conducted a comparative study of diesel, hydro-diesel, and photovoltaic-diesel technologies to evaluate their field performance applying to rural electrification. Kaldellis [11] presented a study of the optimum hybrid photovoltaic based solution for remote telecommunication stations in Greece that lack electric power grids. Hlal *et al.* [12] presented the optimal stand-alone hybrid renewable energy system sizing for a rural settlement using Malaysia's prevalent solar and wind conditions. Rehman and Al-Hadhrami [13] studied a solar photovoltaic (PV) diesel battery hybrid power system for a remotely located population near

Rafha, Saudi Arabia. Tanim *et al.* [14] presented a hybrid energy generation system using solar and biogas energy for supplying energy to remote areas of Bangladesh. Halawani and Ozveren [15] provided a techno-economic analysis for an isolated hybrid power systems (IHPS) that could be deployed for remote, grid-inaccessible areas. Hybrid optimization model for multiple energy resources (HOMER) software was used to study the potential deployment of a hybrid system using photovoltaics, wind turbines, diesel generators, and batteries in Jordan [16]. In another research work, HOMER was used to find the best model for a wind-solar hybrid in Al-Tafila, Jordan [17]. In Bangladesh, Homer was used to study the feasibility of hybrid systems with a combination of biogas, PV, diesel, wind and battery [2]. HOMER was also used to design and simulate a solar-wind-biogas hybrid system in India [18].

Jordan imports 94% of its oil and gas, and its energy consumption rates are growing at a rate of 3% each year [19]. The current electrical generation installed capacity in Jordan is 4.3 GW [20]. The actual contribution of clean energy to total energy consumption is still modest at 7% [19]. Several researchers studied existing case studies or proposed future solutions to energy problem in Jordanian rural areas. Bataineh *et al.* [21] presented a case study of a remote health center in al-mafraq, Jordan that operates 24 hours a day using renewable energy. Masri and Ehsani [22] evaluated the feasibility of integrating wind-PV into the existing utility grid system in Ibrahimiyyah, Jordan. Okonkwo *et al.* [23] showed that a 20 kW PV system and a 10 kW wind turbine are sufficient to support the annual electricity demand of 34.4 MWh for a hotel in Jordan under a stand-alone hybrid system. Rahman and Badran [24] proposed a stand-alone hybrid PV/wind system to continuously power a submersible water pump located at the disi aquifer, south of Jordan. Jarrar *et al.* [25] studied the use of biogas to meet the requirements of farm located in the northern part of Jordan using cow manure.

Based on the foregoing literature review it can be stated that the potential of setting up a hybrid system consisting of PV, biogas, diesel and Wind energy in Jordan has not been studied before. This research aims to design an optimum hybrid renewable energy system that meets the needs of a cow farm with 3,000 cows or similar projects. There is a high potential for the hybrid system to be used in the area of interest due to the extensive presence of renewable energy. Several hybrid systems are presented in this study, and their advantages and disadvantages are compared in order to find the most optimal design. The results will be compared with conventional energy production methods. The importance of this study stems from the importance of highlighting renewable energy in Jordan by opening the door for greater exploitation of natural resources and reducing reliance on conventional fuels using the hybrid PV, wind, biogas systems particularly for remote areas and farms.

2. METHOD

This paper considers Hijazi Farm located in Zarqa, Jordan. It is a cow farm with an area of about 250,000 square meters. The farm is situated at 32°15'19.6"N 36°17'03.5"E. Google maps aerial location is shown in Figure 1. The farm will be scaled up and the cattle count will be increased to 3000. The daily energy load for various uses is 6,000 kWh/day, including vacuum machines used for milking cows, lighting, milk boiling, and other farm daily uses.

Figure 1. Hijazi farm satellite map photo

Figure 2 shows a block diagram of the proposed hybrid system which includes a photovoltaic (PV) system, biogas generator, diesel generator, wind turbine, converter, batteries and charge controller. This research considers all possible combinations of system types in a single run so that a decision about the optimal configuration based on needs and constraints can be made. This requires the following: identification of renewable energy resources (for example, solar irradiation, biomass) in the specified area, estimation of electric load requirements, selection of appropriate components, economic and environmental modeling of the hardware. The required data for simulation was collected from different sources. The farm average daily load profile is shown in Figure 3. The peak load time is from 7.00 am to 11.00 am, especially when working the vacuum machine that operates the cow milking in the farms. Figure 4 shows the average monthly solar radiation (kWh/m^2/day) over 22 years period (1983-2005), along with clearness index averages as collected by NASA's surface meteorology and solar energy database [26]. The annual average GHI is 5.17 Wh/m^2/day, and the clearness index is between 0.485 and 0.679.

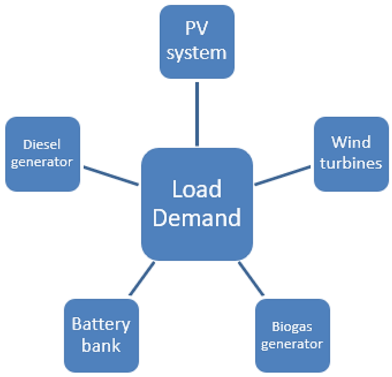

Figure 2. Conceptual block diagram for the hybrid system

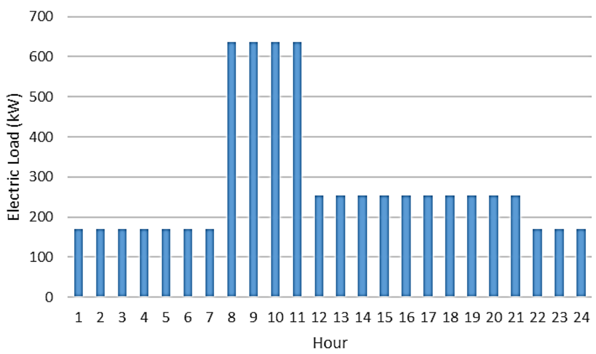

Figure 3. Load profile for Hijazi farm

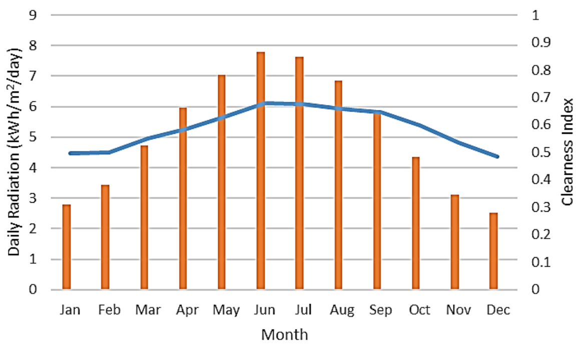

Figure 4. Solar GHI daily profile kWh/day

The farm is located in the Zarqa region, so its altitude above sea level is 500 meters and its anemometer height is 50 meters. For the location of the farm, wind profiles were drawn using NASA surface meteorology and solar energy data covering the period 1983-1993 and presented in Figure 5. Approximately three thousand cows are kept in the farm, which produces the bulk of the biomass on the farm. The production data for the farm is shown in the following table for 2019 year. Every morning, the cowsheds are cleaned of manure with special agricultural machinery that wipes it into underground tanks via trench drains. The trench drains are used to temporarily store the manure so it can be moved later on with a sewage tanker truck equipped with a self-weighing technique so every manure collected is recorded in the farm's logs. The monthly average manure collected from cows is shown in Figure 6.

A hybrid optimization model for multiple energy resources designed for optimizing hybrid renewable energy systems and design known as hybrid optimization model for multiple energy resources, professional version (HOMER Pro) will be used in this study. The study aims to find the least cost equipment combination for consistently meeting the electrical load. Also it aims to study the impact of variables beyond control, such as wind speed, fuel costs, etc, and how these variables affects the optimal system. The data for all components and resources are gathered and inputted into HOMER software in every component field or resource. The final systems are analyzed based on net present cost (NPC) and levelized cost of energy (LCOE) for each system. The software also analyzes all components' performance and percentage share from electricity generation and costs and provides analytics and graphs.

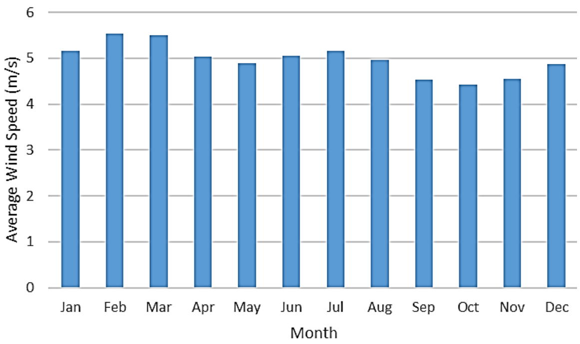

Figure 5. Average wind speed m/s

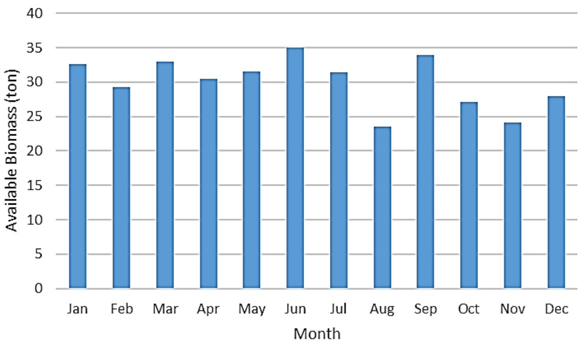

Figure 6. Hijazi Farms reported monthly averages of manure collected from cows

3. SYSTEM COMPONENTS

The study includes PV modules, diesel generators, a biogas generator, batteries, and inverters as main components. This study used a monocrystalline flat plate PV system of the model Jinko Eagle PERC60 300W as it is common in Jordan and available at a good price. The efficiency of this type is 18.33 %. Based on 2020 local prices in Jordan for projects in the range of 0.5-1 MW, the system price is $450 per kilowatt. Operational and maintenance cost per kiloWatt is $1/year. Check-ups and cleaning cost around $1000 annually. Since temperature, dust, and other factors having a changing impact on each panel, the de-rating factor is considered 88% for each panel based on similar projects around Zarqa. A de-rating factor corrects for decreased output resulting from real-world operating conditions compared to those under which a PV panel was rated. The farm under study has an area of 5000 m^2 available for the PV system. In the farm's area, the wind speed is around 5 m/s (11 MPH) which discourages the installation of wind turbines. However, a wind turbine from solid wind group with a model swap-25kw, 25 kW capacity per turbine was considered with a cost of $11000 per turbine. For the optimization stage, a generic gas AC generator with a size of 200, 250, 300, 350 KWh is selected, with a replacement cost of $150 based on Caterpillar prices for Jordan for these types of generators with a minimum load ratio of 30 %, 1800 rpm engine and a lifetime of 20,000 Hour. The generic diesel AC generator is analyzed with the HOMER optimizer to determine the best capacity for each stage, based on Caterpillar prices on Jordan for the specific generator type with a minimum load ratio of 30% and a lifespan of 20,000 hours. In order to convert AC power to DC and vice versa (rectifier and inverter) a generic converter was used. Figure 7 shows the internal flow of electricity through each component in the converter.

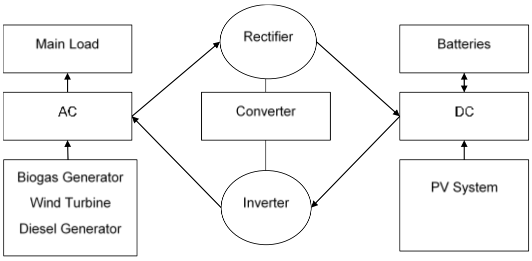

Figure 7. Electricity flow-through system converter

The converter is off-grid with an inverter input efficiency of 90%, and a rectifier input efficiency of 85%. The cost of the system converter and replacement is set at $300 per kilowatt. Trojan's lead-acid battery model SIND 04 was used with a price of $ 1211 and replacement cost of $1000. An optimal controller strategy using a tow-main dispatch policy to control recharging of batteries with renewable energy or generator excess power at required operating time steps based on fixed operating costs for generators (L/hr) and marginal generating costs (L/kWh). Based on the advantages and disadvantages of each strategy, HOMER will choose the best strategy to deploy during optimization. The optimization process took into account economic factors and constraints. Based on the average interest rate of banks in Jordan for these periods of projects a nominal discount rate of 6 % is applied. Given the importance of electricity to the farm, there should be no capacity shortage above 0 %. The lifetime of this project is 25 years.

4. RESULTS AND DISCUSSION

HOMER simulation tool was used to evaluate the performance of different hybrid systems in this study. An analysis of the optimal system configuration was conducted based on an evaluation of the net present cost (NPC) and the levelized cost of energy (LCOE). A total of 5,808 suitable scenarios were found based on component sizes and configurations, after which optimization was used to prune the results down to four feasible scenarios presented in Table 1.

Table 1. Top 4 system configuration based on NPC, LCOE, HOMER output, 2020

#	PV jinko kWp	Wind turbine	Diesel generator kWh	Bio generator kWh	Trojan batteries	Converter kWh	Dispatch type	NPC ($)	Cost/ LCOE ($)/kWh	Operating cost ($)	Initial capital cost ($)	Renewable Fraction (%)
1	1035		940	250	243	663	CC	2,100,291	0.06	67051.24	1243151	94
2	1040	1	940	250	240	649	CC	2,214,752	0.064	67859.06	1347285	94
3	1509			250	550	813	CC	2,259,161	0.065	40278.84	1744263	100
4			940	250	6	12	CC	4,622,848	0.14	338571.7	294764.8	35

The first scenario achieves the best NPC and LCOE. In this scenario, the hybrid system consists of 1035 kWp PV modules, 250 kWh biogas generator, 940 kWh diesel generator, 243 sets of Trojan batteries, and 663 kWh converter. The levelised cost of energy for this choice is $0.06 (JOD 0.042) which is lower than the tariff price for farms in Jordan of $0.084/ kWh (JOD 0.06/ kWh). This leads to a cost saving of $0.024/kWh (JOD 0.017/kWh), which equals a 28% reduction. The total net and operating costs are $2,100,291 and $67051.24, respectively. This system has a capital cost of $1243151. An addition of a wind turbine with a 150 kWh rated capacity (scenario #2) increased the LCOE by $0.004/ kWh (6.25 %) and the NPC by approximately 5% ($114,461). Scenario #3 considered only using renewable energy sources including PV modules, biogas generator, batteries and converter. This choice has a 7.6 % increase in LCOE due to the high cost of batteries. Depending only on diesel generator and biogas generator (scenario #4) will increase the energy price by 57% compared with scenario #1. This is attributed to the high price of diesel in Jordan. Scenario #1 achieved the lowest NPC and LCOE with a high share of renewable energy (94%). Hence, an economic and technical analysis is conducted for this scenario.

The capital costs are estimated to be approximately $1,200,000, with the largest share going to the Jinko PV system ($465,000). An investment of $300,000 will be made in Trojan batteries to store energy at peak hours from the PV system. It is estimated that Biogas generators would cost the least, with $55,000. A detailed breakdown of capital, operating, replacement, salvage, and resource costs is shown in Table 2. The on-grid net present costs percentage from total NPC is shown in Figure 8. After the initial investment cost, there will be a small amount of operating and fuel expense paid yearly, ranging from USD 20,000 to USD 35,000 depending on fuel costs, operating costs, and maintenance costs. Due to the lifetime of the converter, replacement of the converter will cost an addition USD 200,000 at year 15.

Table 2. Breakdown of capital, operating, replacement, salvage, and resource costs

Name	Capital	Operating	Replacement	Salvage	Resource	Total
Diesel generator	$128,780	$31,363	$0.00	-$16,953	$258,024	$401,213
Biogas generator	$55,000	$203,096	$134,703	-$491.48	$159,216	$551,523
Generic boiler	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Jinko PV	$465,961	$13,237	$0.00	$0.00	$0.00	$479,198
Other	$100,000	$38,350	$0.00	$0.00	$0.00	$138,350
Converter	$199,137	$0.00	$83,093	-$15,466	$0.00	$266,763
Trojan SIND 04	$294,273	$0.00	$0.00	-$31,692	$0.00	$262,581
System (All)	$1.24M	$286,045	$217,795	-$64,603	$417,902	$2.10M

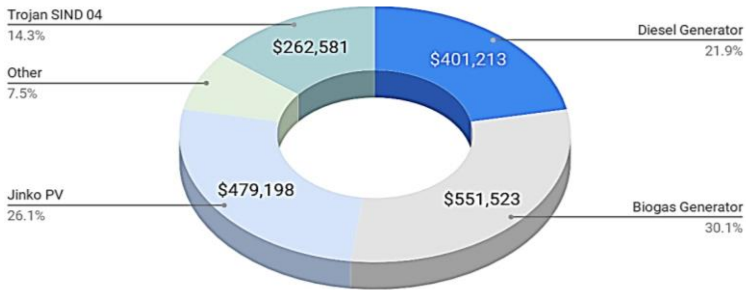

Figure 8. On-grid net present costs percentage from total NPC

A comparison of the cumulative cash flow for the best and base case scenarios is shown in Figure 9. It is clear that the best-case scenario outperforms the base case in terms of slope rate and total cumulative cash flow despite the fact that the base case capital investment is significantly higher than the base system. The base case, however, has a higher operational cost and fuel cost result in a higher total cumulative cash flow than the best-case scenario.

Based on the best-case scenario, solar energy would provide 1,870,001 kWh/year (57.9%), biogas would provide 1,267,853 kWh/year (39.2%), and diesel would produce 93,982 kW/year (2.91%). In fact, this exceeds the farm's needs (2,130,140 kWh/year) by about 21%. The diesel generator is the conventional power source in the system, fired with fossil fuel resources. It is available 24x7, but costs much more than renewable energy sources. An estimated 20% of the initial and running costs of the system NPC are due to the cost of the diesel generator and the high price of fuel. Despite producing only 3 percent of the total electricity over the year, the importance of the diesel generator comes to meet the high load needed, especially during peak hours in the farm where other sources cannot cover the needed load. The HOMER simulation showed the generator works sporadically throughout the year in a range of 200 kWh to 500 kWh between 6.00 am and 12.00 pm. Since the generator works only 261 hours per year, the life of the generator could be extended up to 57.5 years, according to the manufacturer. Biogas has the advantage of low storage costs, so instead of using expensive batteries at night or on cloudy days, it is used primarily on farms that make use of cow manure. The biogas generator is fueled by cow manure and consumes approximately 90% of the yearly cow manure production.

The generator runs for 6355 hours/year, so its operational lifetime is around 3 years according to the manufacturer of the generator. During the hours when PV is not working, primarily 6 pm to 6 am, the biogas generator is used to reduce the dependency on expensive batteries during this period, as storing biogas costs less than batteries. PV is the least expensive electrical source in the system with a levelized cost of $0.02/kWh. In Jordan, the PV array generates energy in the sunny hours with around 300 days a year from 6.00 AM to 6.00 PM, and the peak production time occurs at 11.00 AM to 2.0 PM. The system produces about 1,850,000 kWh/year. In nights and on cloudy days, due to the lack of sunrays and power storage, other energy producing systems must be used to satisfy the load requirements of the farm. Batteries play a balancing role in the system, as the whole year's state of charge ranges between (85-95%). The converter is only operating at about 20% of its rated capacity with a mean output of 131 kW, compared to 664 kW rated capacity. The most flow in the system is from DC to AC through the inverter. This represents the flow of PV and batteries electricity to supply AC loads of 250-650 kWh. The rectifier on the other hand represents the flow of electricity from Generators to batteries to store the power. The flow through the rectifier is usually between 0 and 60 kWh around the year. The environmental benefits are evaluated based on the base case and the best-case power generations. Table 3 compares base and best-case scenarios with regard to greenhouse gas emissions. As shown in the Table 3, around 92 % of emissions can be avoided annually, with more than 743,124 kg CO_2 emissions.

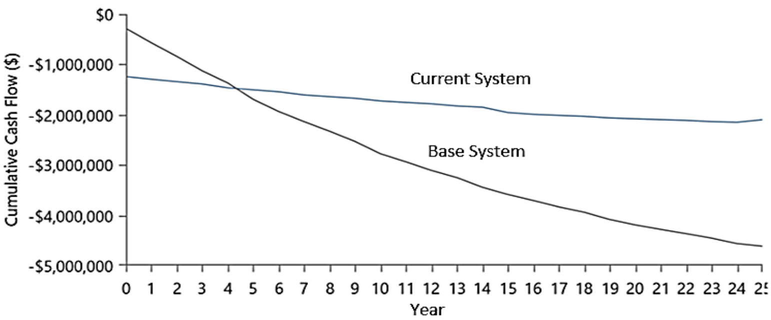

Figure 9. Cumulative cash flow, base case Vs best case

Table 3. Comparison of base case and best case greenhouse gas emissions

Pollutant	94 % Renewable	36 % Renewable	%	Unit
Carbon Dioxide	70,590	813,714	8.67	kg/yr
Carbon Monoxide	452	5,139	8.79	kg/yr
Unburned Hydrocarbons	18.9	223	8.47	kg/yr
Particulate Matter	2.62	31	8.45	kg/yr
Sulfur Dioxide	168	1,988	8.45	kg/yr
Nitrogen Oxides	419	4,820	8.69	kg/yr

5. CONCLUSION

This study examined the feasibility of using an off-grid hybrid energy system to generate electricity for a farm containing 3,000 cows using HOMER Pro software. Several hybrid systems were analyzed based on NPC and LCOE. The optimized hybrid system consists of PV modules, biogas generator, diesel generators, batteries and inverter. PV modules have the largest share of the energy production. The use of biogas generators reduces the need for expensive batteries during those hours when PV systems are not functioning. Diesel generators are installed in the farm in order to meet high load demands during peak hours when other sources of power cannot cover the demand. The LCOE for the optimal configuration is $0.06 /kWh. Furthermore, the proposed system has attractive environmental benefits.

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