

Article

Optimum Configuration of a Renewable Energy System Using Multi-Year Parameters and Advanced Battery Storage Modules: A Case Study in Northern Saudi Arabia

Abdullahi Abubakar Mas'ud ^{1,2,*}  and Hassan Zuhair Al-Garni ¹ 

¹ Electrical and Electronic Engineering Technology Department, Jubail Industrial College, Al Jubail 35718, Saudi Arabia; garnihz@gmail.com

² Prince Saud bin Thunayan Research Centre, Royal Commission for Jubail, Al Jubail 35718, Saudi Arabia

* Correspondence: masud_a@jic.edu.sa or abdullahi.masud@gmail.com; Tel.: +96-65-3813-8814

Abstract: Understanding the impact of global warming and the availability of renewable sources has motivated many countries to utilize solar and wind as an alternative to conventional energy sources. One country at the forefront in the development of these technologies is the Kingdom of Saudi Arabia (KSA). In KSA, investing in wind and solar energy is important because the country's load demand is rapidly increasing, coupled with the over-reliance on fossil fuels. By fully utilizing the multi-year and the advanced battery storage modules in HOMER, in this paper, the techno-economic viability of utilizing a PV/wind/diesel/battery system for a remote location of Al-Jouf in the KSA has been investigated. The novelty of the work presented in this paper is that for the first time a PV/wind/diesel/battery system has been designed for the KSA, taking into account the impact of multi-year and advanced battery storage parameters such as the increase in fuel price, PV degradation, increase in the consumer load and battery degradation. Besides, due to the high temperatures experienced at Al-Jouf during the summer season, this paper investigates the sensitivity of ambient temperature on the system's performance. The result shows that the multi-year input and battery degradation parameters have a significant impact on the system output over the 25 year lifetime of the project. PV production has dropped by 11.3%, while diesel production rose to 38% thereby increasing fuel consumption and CO₂ emission. The system's LCOE and NPC are 0.204 and USD206,919 respectively. According to the sensitivity analysis, ambient temperature has a significant impact on battery performance and PV power generation.

Keywords: PV; wind; battery; diesel; renewable energy sources; HOMER; multi-year inputs



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1. Introduction

In many countries, fossil fuels are regarded as one of the main energy sources; however, producing power from such fuels is an essential source of greenhouse emissions that can adversely affect the environment [1]. The increasing depletion of fossil fuel resources globally, coupled with a significant rise in energy demand, is the other reason why reliance on fossil fuels should be minimized [2]. To address the abovementioned challenges relating to conventional power generation techniques, renewable energy sources (RES) are considered as an alternative and have now generated a lot of attention [3]. Among the RES, solar and wind are environmentally friendly and not exhaustible [4]. According to the 2019 global status report on RES, the global composition of the installed renewable energy capacity is continually growing [5]. Wind power increased to about 25% of the installed renewable power capacity, while for the first time solar photovoltaic (PV) exceeded 20%. Generally, RE contributes about 33% to the installed capacity of the global power generation. Figure 1 compares the global power generating capacity between renewables and non-renewables between 2008 to 2018.

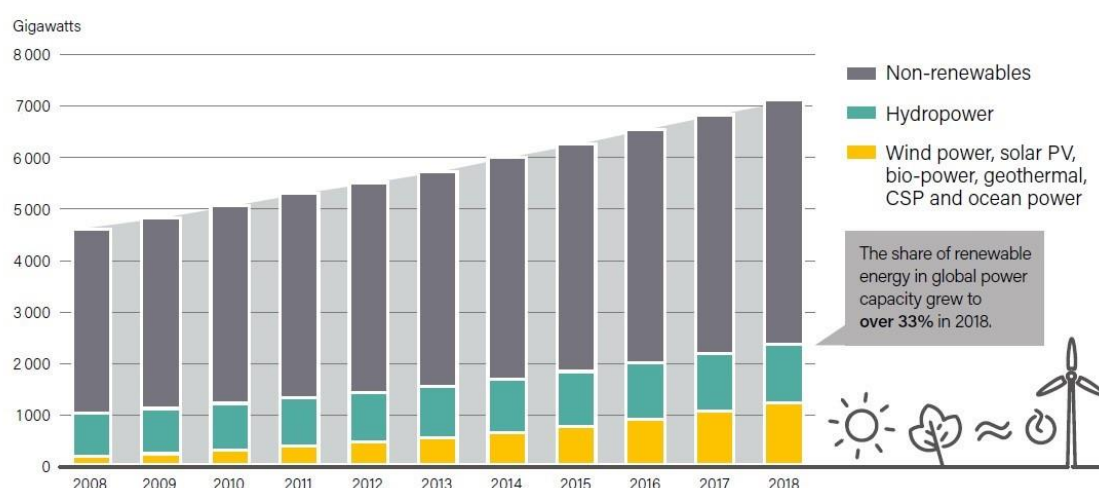


Figure 1. Global power generating capacity by source 2008–2018, Adapted from [5].

In general, among the RES, solar and wind are the preferred options that can be used in the distributed electricity system. Due to the intermittent nature of renewable power sources, it is important to integrate them with other conventional energy sources to provide a more reliable power system. They can be utilized to supply green energy to rural communities. The Kingdom of Saudi Arabia (KSA) has immense solar potential. It is situated in the global sunbelt, which is a geographical region between 35° N and 35° S that is generally recognized for its high solar energy [6]. The solar irradiance in KSA is among the highest in the world, with the yearly average global horizontal irradiance (GHI) estimated at 5700 Wh/m² to 6700 Wh/m² [7]. Besides solar, several researchers have indicated that wind energy can be a viable energy source for the KSA, as in other places, with an annual average wind speed above 4 m/s, estimated at 20 m above the ground level [8]. Generally, in most parts of the KSA, the annual average wind speed was recorded to be between 6.0 and 8.0 m/s, at 100 m above the ground [9,10]. The coastal city of Yanbu has the highest wind speed of about 9 m/s, followed by Al-Jouf and Hafr batin with a wind speed of 6.3 m/s [11]. In terms of solar energy, Sharurah appears to have higher solar radiation as compared to others, but generally, for most locations, the solar radiation is more than 6000 Wh/m² [12]. Despite all these developments, the current implementation of RES is incomparable to its potentials, although the government has already put plans to enhance the renewable energy sector in the coming years. Like any other country, Saudi Arabia is trying to find alternative energy sources to support the Saudi 2030 vision of electricity production by using RES [12]. The country has set a target of 41GW from RES by 2032 [13]. However, there are already some projects of solar and wind in some parts of the KSA mainly for standalone applications [14]. The implementation of these projects began to accelerate and to see the light of the day. The Sakaka solar PV project with a capacity of 300 MW was built in 2017 to generate electricity and was recently connected to the grid, while the 400 MW wind project at Dumat Al-Jandal recorded the lowest levelized cost of energy (LCOE) worldwide. In 2019, the second phase started, which consisted of 1470 MW PV projects spread out over six cities, i.e., Medina, Rafha, Al Qurayyat, Rabigh, Jeddah and Taif, with a minimum of 50 MW per project [15].

Several studies have been undertaken in the KSA to design hybrid RES for power generation [16–18]. In particular, Ramli et al. investigated the application of PV/wind for a coastal region of the KSA [17]. They focused on the electricity generation and energy cost using hybrid PV/Wind. Two popular software packages, i.e., MATLAB and HOMER were utilized for the techno-economic analysis of the scheme. The result shows that the PV generates more power than the wind if both of them are used in a hybrid system. The batteries and the wind turbine account for the majority of the system's total cost. In another study, Ramli investigates the feasibility of hybrid PV/Diesel for the west coast

of the KSA [19]. HOMER was utilized for the techno-economic analysis of the system. Three schemes were compared namely hybrid PV / diesel / battery, hybrid PV / diesel and the diesel-only system. Among them, the PV / diesel / battery outperforms the others with an LCOE of USD0.117/kWh and 15% PV penetration. Another study conducted by Rehman et al. investigated the application of a PV / diesel system with battery backup for a remote location of the KSA [20]. At a diesel price of USD0.2 per liter, energy prices for diesel only and PV / diesel / battery power systems with 21% solar penetration were found to be USD0.19 per kWh and USD0.219 per kWh, respectively. However, in all the previous studies on RE for the KSA, simulations were conducted for an entire lifetime of the project without considering PV, battery degradations, and or diesel price fluctuations over time. These parameters are important as they can improve the reliability of simulation results for both current and future projects. For PV, degradation can play an important role in evaluating its performance. The PV can degrade over time due to temperature changes, precipitation, dust, humidity etc. [21], while batteries can also degrade due to the continuous charging and discharging. It is also known that diesel price changes over time can significantly affect the long-term cost of the RES.

Recently, KSA has embarked on the development of a wind farm in the Al-Jouf region in the northwestern part of the country [22]. Vestas (V150) wind turbines, each rated at 4.2 MW, will make up the wind farm. This paper investigates the techno-economic and environmental feasibility study of an off-grid PV / wind / diesel / battery hybrid system for a rural community in the Al-Jouf region using HOMER's multi-year and advanced storage modules, in which the analysis is assessed yearly over the project's entire life cycle. The overall aim is to investigate whether the yearly degradation of the PV, battery and diesel price variations can affect the system's net present cost (NPC), LCOE and carbon emissions etc., the increments and decrements of the load growth will also be considered. Al-Jouf, (see Figure 2), is a province situated at the northern part of Saudi Arabia, with its only international border to the west of Jordan. The region has an area of 100,212 km², and as of 2017, it has a resident population of 508,475 [23]. PV and wind data used in this paper were based on ground measurements from King Abdullah City for Atomic and Renewable Energy (KACARE). In order to obtain accurate results, site-specific parameters for the city of Al-Jouf will be used in the simulation such as ambient temperature, hub height, altitude and ground reflectance, etc.



Figure 2. Map of the KSA showing the Al-Jouf region (Sakaka), Adapted from [24].

2. Importance of Multi-Year Approaches

In the design of any project with RES, quantifying accurately the power decline over time and the associated varying economic factors is crucial to all stakeholders including governments, utility firms, investors, and researchers. Thus, assessing the changes that can occur on a yearly basis over the course of a project can help evaluate the project's economic viability. Grid price rise, load growth, fuel price fluctuation, battery and PV degradation are parameters that will transform into lower cash flows or less power generation [25]. Obviously, the techno-economic study of a system with RES that does not take into consideration such factors is investigating the system with inadequate information. However, most studies use a single year as a measure of the entire lifespan of the project and take decisions based on the energy situation in that year alone [26]. Thus, the purpose of this work is to take full account of the multi-year changes in the component parameters of an Al-Jouf hybrid RE project in order to arrive at the most economical solution.

3. Methodology

This paper is intended to provide key information on the application of PV/wind/diesel/battery system for off-grid applications in the KSA's Al-Jouf region. The investigation was performed using the HOMER [27], taking into account various techno-economic measures. The performance of the system at a given location as opposed to the performance of the system under theoretical operating standards is demonstrated by certain metrics.

The HOMER software has been extensively used for the design and techno-economic evaluation for power networks incorporating RES [27,28]. There are several parameters required by the HOMER as inputs such as the data of all RES, load profile, cost of the energy sources, dispatch strategies and economic constraints. The HOMER develops an optimized power scheme to meet the chosen load. To get the best match between supply and demand, HOMER repeatedly performs thousands of hourly simulations. The following section explains the methods, strategies, and assumptions made in carrying out the techno-economic analysis.

3.1. Load Profile

Saudi Arabia's Al-Jouf region is well known for its abundant water, which makes it possible to grow dates and other agricultural products. Therefore, during daytime, most people are either at their place of work or farm. Then it is clear that the daytime load demand would be much lower than that at night. The load is an important factor for any power generation scheme and has a major impact on the system design. In this study, residential loads will be considered. As of 2018, the monthly average bill for one apartment is shown in Figure 3. The summer season from May to August indicates a fairly high energy consumption due to excessive utilization of air conditioners. The mean yearly power consumption is 160 kWh /m² /year. From the literature, it has been shown that the load demand for two apartments for the KSA would be a fair representation of numerous remote apartment blocks without access to the grid. In this work, the aforementioned load will be utilized for the PV/wind/diesel/battery scheme at the Al-Jouf region (see Figure 4). It can be noted that the peak load is 26.53 kW with a daily average load demand of 165.44 kWh/day. An expensive alternative may be to deliver power to these rural communities by diesel generators alone, or through the country's grid. The deployment of RES together with diesel generators will lead to lower fuel consumption and engine emissions, thereby providing longer life to the diesel engines.

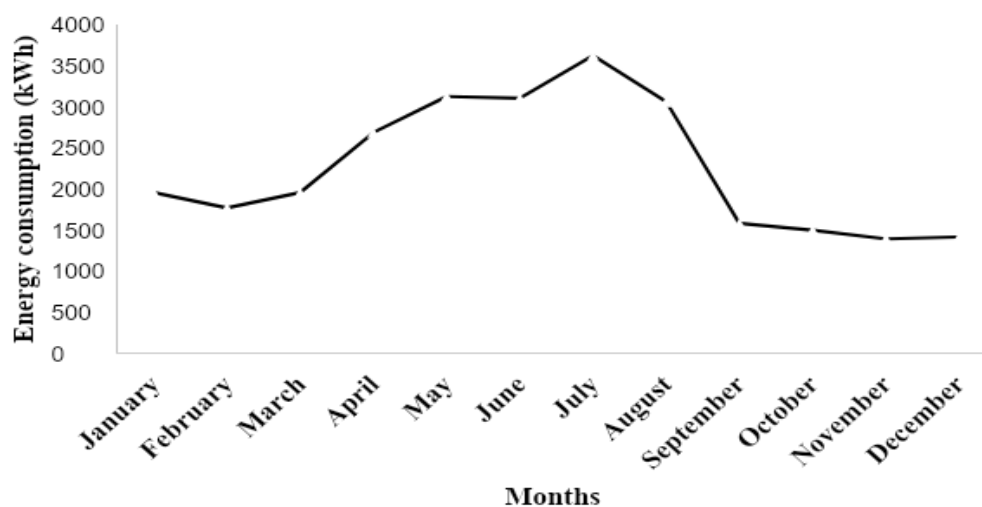


Figure 3. Monthly energy consumption for a residential area in KSA (2018), Adapted from [29].

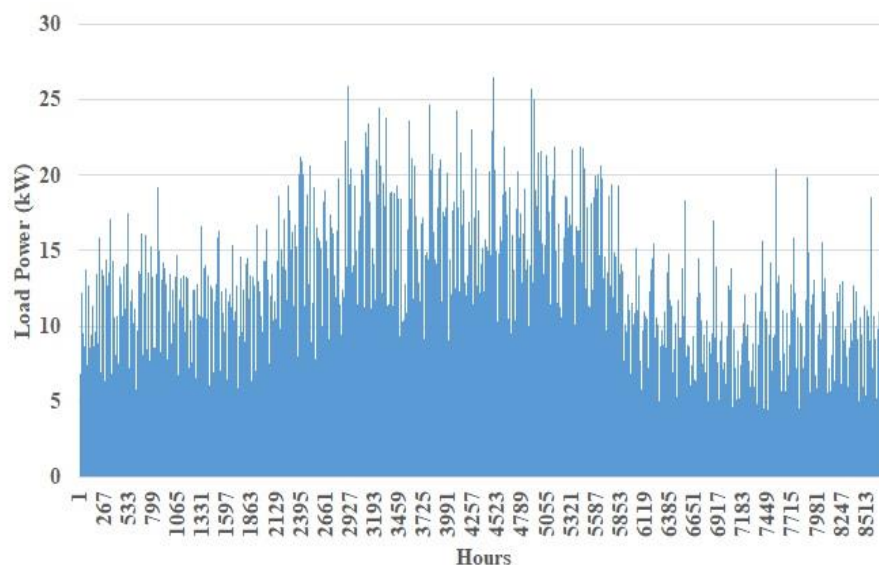


Figure 4. hourly Load demand for a remote location at Al-Jouf.

3.2. Solar Energy Resources

For any PV system, two key parameters determine its performance i.e., solar irradiation and ambient temperature. HOMER utilizes these two parameters as its input. The PV power generation can be calculated using the equation below [30]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_p (T_C - T_{C,STC})] \quad (1)$$

where Y_{PV} represents the PV output under normal operating conditions (kW), G_T represents incident solar radiation at the standard temperature condition in kW/m^2 , f_{PV} is the derating factor of the PV array, α_p denotes the temperature coefficient of power measured in $^{\circ}\text{C}$, T_C represents the temperature of the PV in $^{\circ}\text{C}$ and finally $T_{C,STC}$ denotes the PV array's temperature at the standard temperature conditions (i.e., 25°C).

In the present study, hourly and monthly solar energy profiles for Al-Jouf was obtained from KACARE. The Al-Jouf region lies within 29.89°N latitude, 39.32°E longitude [31], and its monthly solar insolation ranges between $3614\text{--}8453.7\text{ Wh}/\text{m}^2$. From Figure 5, the summer months (i.e., May–August) have higher solar radiation as compared to the others. It is an indication of a likely higher solar power during the summer periods, which correlates

with the higher energy demand at that period. This area apparently has enormous solar potential and could be a suitable site for electricity through solar energy. The ambient temperature of Al-Jouf is shown in Figure 6. The highest temperature consistently occurs within the months of May and August. The average peak ambient temperature is 43 °C in June/July while the lowest temperature of 24 °C occurs in the month of January.

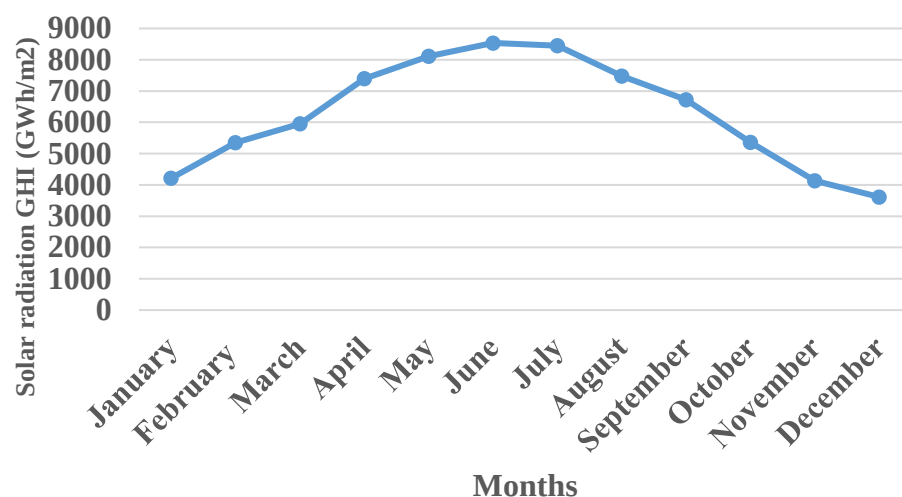


Figure 5. Hourly solar radiation for Al-Jouf, Adapted from [32].

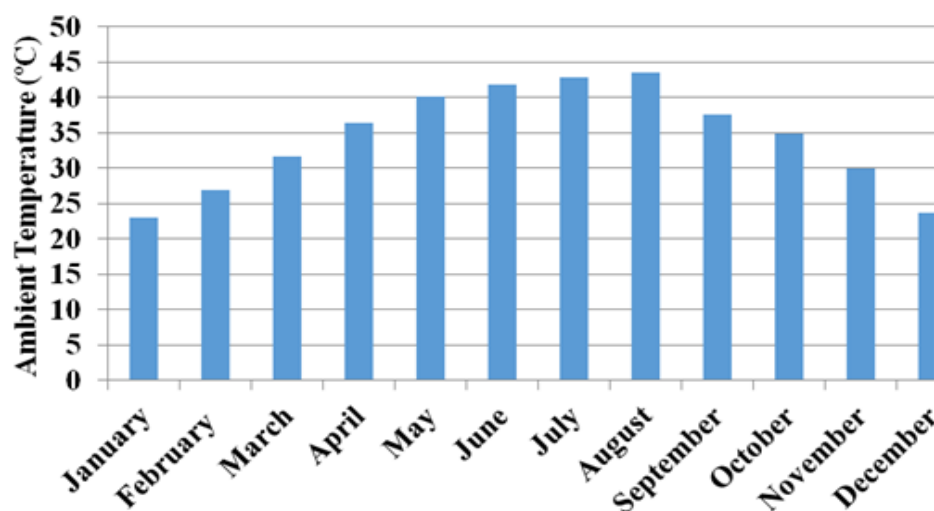


Figure 6. Monthly average ambient temperature of the Al-Jouf, Adapted from [32].

3.3. Wind Energy Resources

The HOMER software computes the wind turbine power output using three steps [33]. First, it calculates the wind speed based on wind turbine's hub height. Second, it determines the wind turbine's power based on the wind speed at normal air density, from where the wind power output under the actual air density can be determined. HOMER determines the wind speed of the wind turbine at each phase of the process using user inputs from the wind resources. The HOMER can then obtain the hub height wind speed based on either the power or logarithmic law [33]. In this study, the logarithmic law was chosen. By assuming a rough pasture, a surface roughness length of 0.01 m will be used.

$$U_{hub} = U_{anem} \frac{\ln\left(\frac{z_{hub}}{z_0}\right)}{\ln\left(\frac{z_{anem}}{z_0}\right)} \quad (2)$$

While the power law equation is represented by:

$$U_{hub} = U_{anem} \left(\frac{z_{hub}}{z_{anem}} \right)^\alpha \quad (3)$$

where U_{anem} = speed of the wind measured in m/s, at the anemometer height, U_{hub} = speed of the wind measured in m/s, at hub height of the turbine, z_{anem} = the wind turbine's anemometer height measured in meters, z_{hub} = the wind turbine's hub height measured in meters, z_o = the surface roughness in meters and α = represents the power law exponent.

In HOMER, the wind speed is measured based on the hub height while turbine power curve is utilized in determining the wind power. The average monthly wind speed for the design of the hybrid system at Al-Jouf, will be part of the input to the HOMER (see Figure 7). The wind speed for Al-Jouf lies within the ranges of 6.4–7.6 m/s. It appears to be lower in March and higher in January. The wind speed at Al-Jouf lies within Class 4, which is sufficient to generate electricity [34].

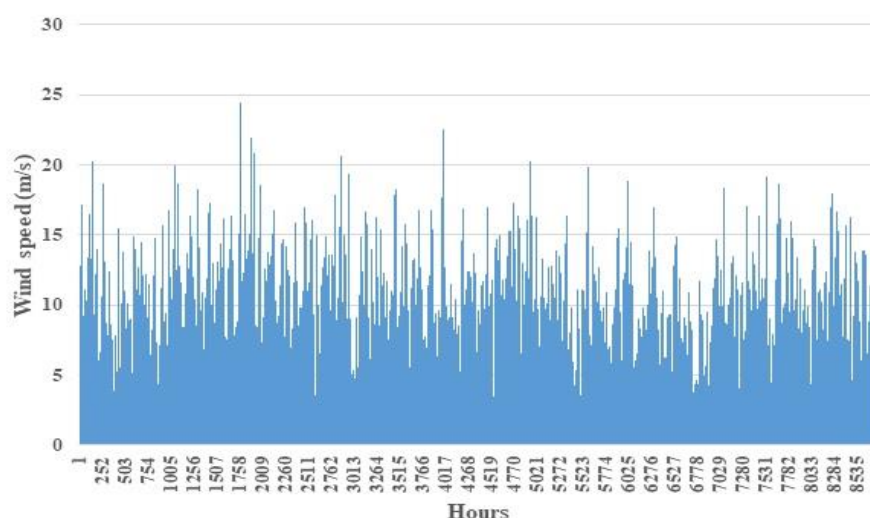


Figure 7. Hourly wind speed for the selected region as approximated by HOMER [33].

3.4. Economic Considerations

The main objective of HOMER is to find the best possible configuration and reduce the operating cost of the system. The economic model for the simulation of HOMER is based on the NPC. The NPC sums all costs and revenue growth over the project's lifetime. It is defined by:

$$NPC_{total} = \frac{C_{an,total}}{CRF(i, P_L)} \quad (4)$$

where CRF denotes the function associated with capital recovery, $C_{an,total}$ denote the total annualized cost, P_L is the project's lifespan, i represents the percentage yearly interest rate and the CRF is defined as follows [35]:

$$CRF(i, m) = \frac{i(1+i)^m}{(1+i)^m - 1} \quad (5)$$

where m represents the lifespan of the project. In the calculations, HOMER uses the average real interest rate in all calculations. Nevertheless, the annual real interest rate can be determined as follows:

$$i = \frac{i' - f}{1 + f} \quad (6)$$

where f denote the inflation rate, i' is the yearly nominal interest rate and i represents the yearly real interest rate. The system's average cost per kWh of available energy is referred

to as the LCOE. It is ratio of the annualized cost of power generation (C_T) to the overall electrical load served (E_T) as shown below:

$$\text{LCOE} = \frac{C_T}{E_T} \quad (7)$$

4. System Inputs

Five key components are used in the simulated system, namely the wind turbine, PV module, diesel generator, battery storage and converter. Each of these components has certain types of parameters such as the power rating, capital cost and lifetime that are useful as input to the HOMER. Table 1 lists the technical specifications selected for the complete system. To ensure a robust analysis, the multi-year inputs in HOMER are utilized. Such inputs to be considered are the yearly PV degradation rate, load growth rate and diesel price fluctuations. The overall aim is to model the yearly degradation of the PV and battery, variations in the load and the diesel price fluctuations. For the proposed PV/wind/diesel/battery scheme, a schematic diagram is shown below (i.e., Figure 8).

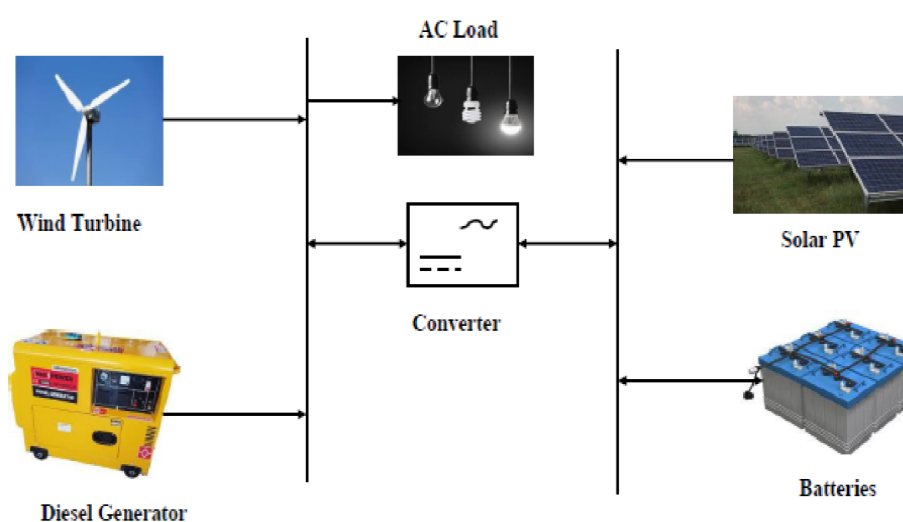


Figure 8. The proposed PV/wind/diesel/battery scheme for Al-Jouf.

Table 1. Input parameters for the HOMER and their corresponding specifications.

Component	Descriptions	Specifications
PV system	Nominal efficiency	18% [29]
	Nominal operating cell temperature	47 °C [21]
	Tracking system	No Tracking
	Panel slope	33° [28]
	Panel Azimuth (West of South)	144° [28]
	Temperature coefficient	−0.4%/°C [36]
	Derating factor	80% [37]
	Capital cost of the PV	659.60/kW [38]
	Cost of PV replacement	659.60/kW [38]
	Operating and maintenance cost of the PV	USD10/kW/year
	Lifetime	25 years [39]

Table 1. Cont.

Component	Descriptions	Specifications
Diesel generator	Capital cost	USD220/kW [40]
	Lifetime	15,000 h [1]
	Operating and maintenance cost	USD0.03/kW/hr [21]
	Replacement cost	USD220/kW [40]
	Fuel price	0.125/Litre [41]
Wind turbine	Model	Generic 3 kW
	Replacement cost	USD18,000/kW [17]
	Capital cost	USD18,000/kW [17]
	Hub height	80 m [33]
	Lifetime	20 years [8]
	Operation and maintenance cost	USD180/kW/year [17]
Batteries	Model (before multiyear)	Lead acid [2]
	Nominal capacity (Before multiyear)	1 kWh [42]
	Nominal voltage (Before multiyear) i.e., (Voltage per string)	12 V [42]
	Maximum capacity(Before multiyear)	83.4 Ah
	Estimated Throughput	800 kWh
	Battery replacement time	10 years
	Model (Multiyear)	Lead Acid (ASM)
	Nominal voltage (Multiyear) i.e., (Voltage per string)	2 V
	Maximum capacity(Multiyear)	513 Ah
	Nominal capacity(Multiyear)	1.03 kWh
	Operating and maintenance	USD10/year
	Estimated Throughput	843 kWh
	Capital cost	USD300 [39]
	Replacement cost of the battery	USD300 [39]
	Efficiency	85% rectifier, 90% inverter [21]
Converter	Capital cost of the converter	USD550/kW [43]
	Replacement cost of the converter	USD450/kW [21]
	Operation and maintenance cost of the converter	USD10/kW/year [43]
	Lifetime	15 years [19]
	Nominal discount rate (%)	6.86
Control parameters	Project lifetime	25
	Inflation rate	2.5
	PV degradation	0.5%
Multi-year inputs	Diesel price fluctuation	1%
	Load growth	1%

5. Results and Discussion

HOMER is used in this paper to achieve the optimal combination of hybrid system with RES corresponding to the northern part of Saudi Arabia, i.e., the Al-Jouf region. A viability study on the various systems including environmental factors has been examined.

In order to arrive at the most feasible solution, a sensitivity analysis was performed to observe the effect of certain input parameters on the output of the system.

5.1. Optimization Results Based on the LCOE

To satisfy the load, all the possible combinations of the PV/wind/diesel/battery system were evaluated by HOMER, considering a system lifetime of 25 years. In this study, it is intended to choose the one that at least comprises of all the possible components. All the feasible combinations were sorted and the one with the lowest LCOE and NPC chosen (see Table 2). The results indicate that a combination of the following components i.e., 24.5 kW PV, 27.0 kW diesel generator, 12 strings of batteries, 3 kW Generic wind turbine, 13.0 kW converter, is the most feasible solution based on LCOE of USD0.2089 and the NPC of USD191,943.9. The system has a capital cost of USD50,850.2, operation and maintenance cost (OMC) of USD66,793.83, replacement cost of USD51,031.57, fuel cost of USD30,085.38 and a salvage cost of USD6817.12 (see Figure 9). After installation of the system, the OMC of wind turbine, PV and battery are extremely low, while the diesel generator contributes 78% of the total OMC. The PV does not require any replacement because it has the same lifetime as the complete system. No fuel is consumed in the PV, batteries and the converter. The diesel generator is therefore responsible for the total cost of the fuel. The system's salvage value is obtained from the remaining lifetime of the generator, battery, converter and the wind turbine.

Table 2. Feasible combinations of RES based on the HOMER Simulations.

Architecture					NPC (USD)	LCOE(USD)
PV (kW)	Number of 3 kW Wind Turbines	Diesel Generator (kW)	Number of Batteries (1 kWh)	Converter (kW)		
24.5	1	27.0	12	13.0	191,943.9	0.2089
34.4	1	27.0	-	13.1	210,274	0.229
-	-	27	12	2.67	214,326	0.233
-	-	27	-	-	217,569	0.237
-	1	27	15	2.90	224,074	0.244
-	1	27	-	-	237,187	0.258
81.3	3	-	309	22.6	397,105	0.433
139	-	-	393	24.9	452,972	0.493
-	19	-	1215	38.4	1,370,000	1.492

In Figure 10, the monthly average electricity generation is shown. Diesel generators and PV arrays provide the highest electricity demand (i.e., 43.2% for the PV and 46.5% for the diesel generator), while the wind turbine produced 10.3% of the overall energy demand. Most of the demand is satisfied by the PV and diesel generator, with little contribution from the wind turbine. Owing to the high cost of installing wind turbines and other hybrid system components, it is important to consider reducing their energy contribution at all times. Also, more wind turbines in a system might increase the LCOE and the NPC, and in some cases making the project not economically viable in the long run. The system has an excess energy of 17,433 kWh/yr and can be reused to satisfy other loads associated with the heating and cooling of households.

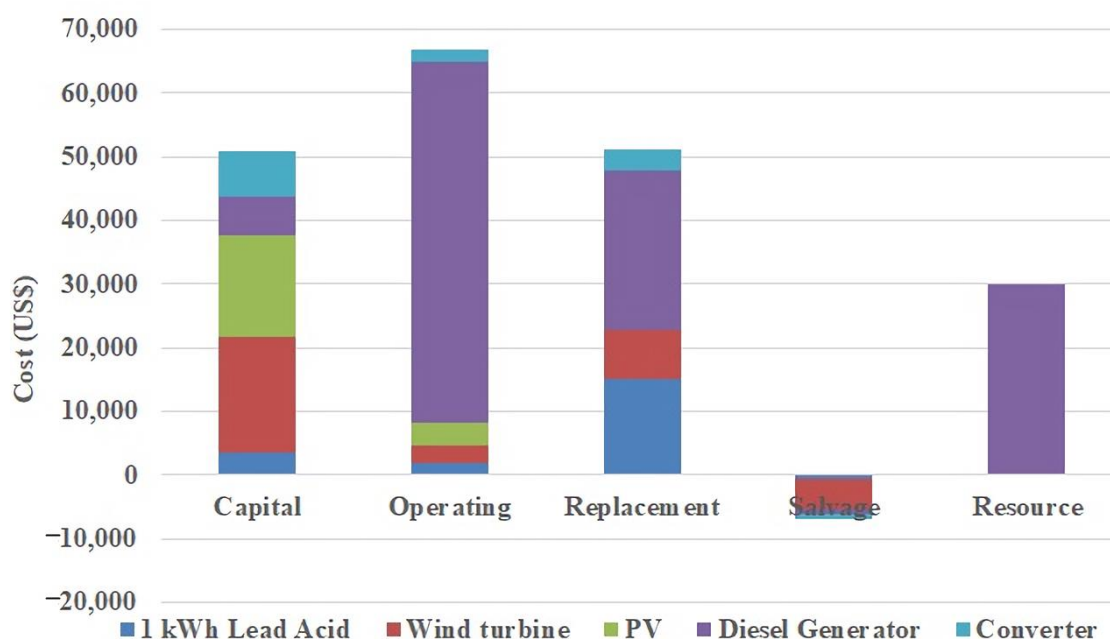


Figure 9. The summary cost of the PV/wind/diesel/battery scheme for the Al-Jouf region.

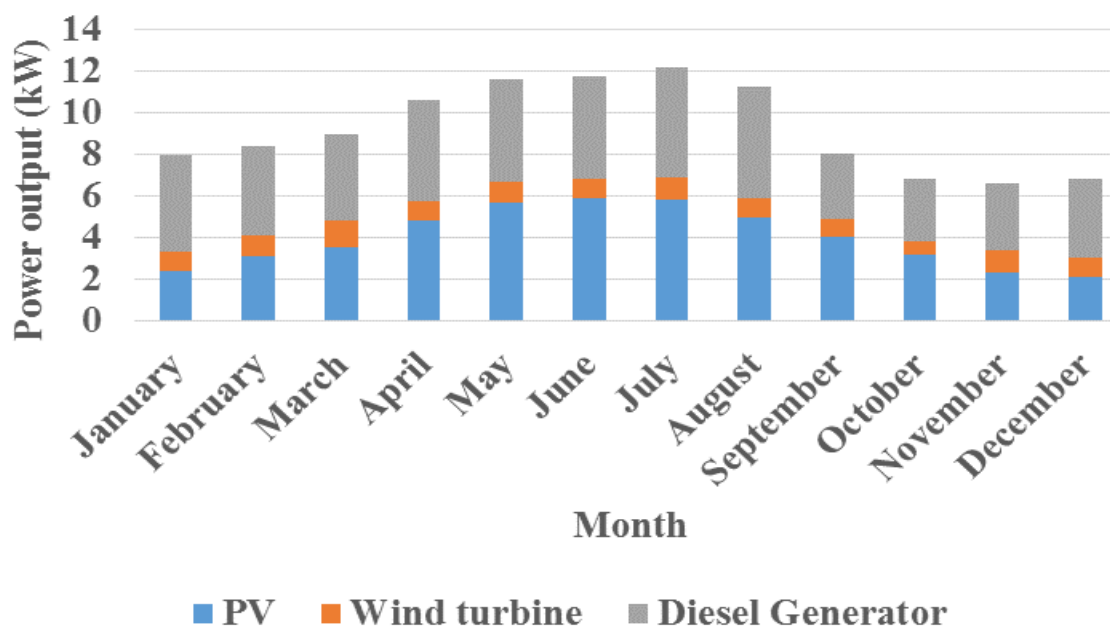


Figure 10. The average monthly Electrical power generation by source.

5.2. Influence of the Multi-Year and the Advanced Battery Storage Parameters on the System performance

In this section, the influence of the HOMER multi-year and the advanced battery storage parameters on the system's performance will be evaluated. Figure 11 shows the effect of the HOMER multi-year parameters on the wind turbine, PV, battery output, diesel production and CO₂ emission over the complete project lifespan. Consequently, the diesel generator output rises from 35,419.86 kWh/year to 49,523.74 kWh/year during the 25-year period, while the PV output decreases from 34,960.7 kWh/year to 30,998.03 kWh/year. The yearly rise in the diesel generator power output is due to the continuous rise of the load and degradation of the PV. It is noted that an increase in diesel consumption resulted in an increase in the emissions of CO₂ from 36,667.9 kg/year to 49,355.03 kg/year. In

addition, the produced energy of the batteries shows several variations over the lifespan of the project due to the timely replacements of the batteries. As expected, after the 25-year period, the LCOE and the NPC are 0.2033 and USD206,593.70. The NPC value is higher than the case without the multi-year module, indicating that the inclusion of the multiyear parameters has shown more precise cost analysis.

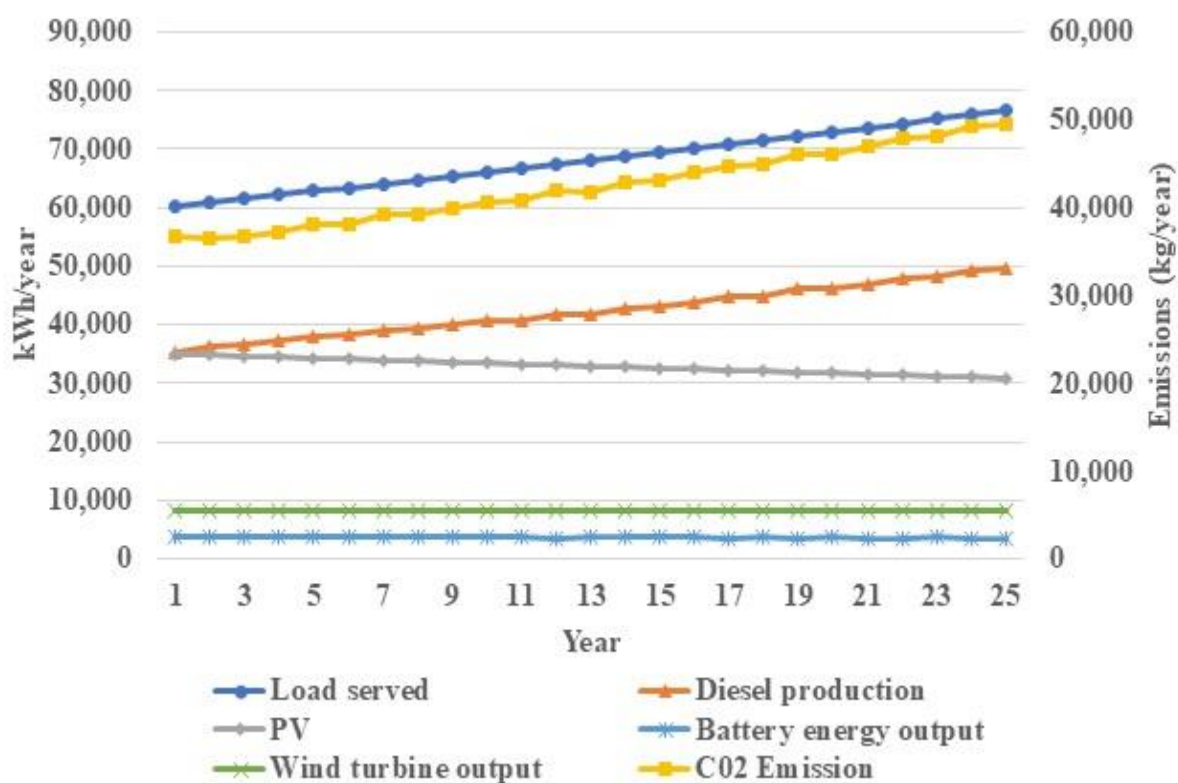


Figure 11. The system characteristics under the multiyear module.

In this section, further details are provided about the degradation of the battery. For this analysis, the modified kinetic battery model was chosen. Two forms of degradation occur throughout its lifespan of the project. The first degradation is associated to the wear of cycles adjusted for the depth of discharge. In essence, it tracks the cycle fatigue on the battery also known as cycle degradation. Time and temperature over the life of the battery are associated with the second degradation. If the battery is idle or is being used, for each step, the deterioration of the storage element increases. The rate of increase is only dependent on the temperature. Figure 12 displays the battery calendar and cycle degradations, along with the equivalent cycles of the battery over the entire project lifetime. By the end of the lifespan of the battery, the cycling degradation contributes approximately 20%. Meanwhile, for this time calendar degradation (i.e., due to time and temperature) is just around 0.01%. In addition, after 823 equivalent cycles, the batteries need to be replaced.

The battery throughput is an important parameter that determines the lifetime of the storage bank. It represents the yearly amount of energy stored in the battery bank i.e., after charging and before discharging losses. It is apparent that an increase in fuel consumption resulted in a reduction in battery capacity, thus improving the battery lifetime. Furthermore, over the 25-year project lifetime, there is a slight decrease in excess energy and RE fraction in the micro-grid (Figure 13). The decrease in excess energy and the fraction of RES is due to the continuous PV degradation, although not significant enough to have any meaningful impact on the system.

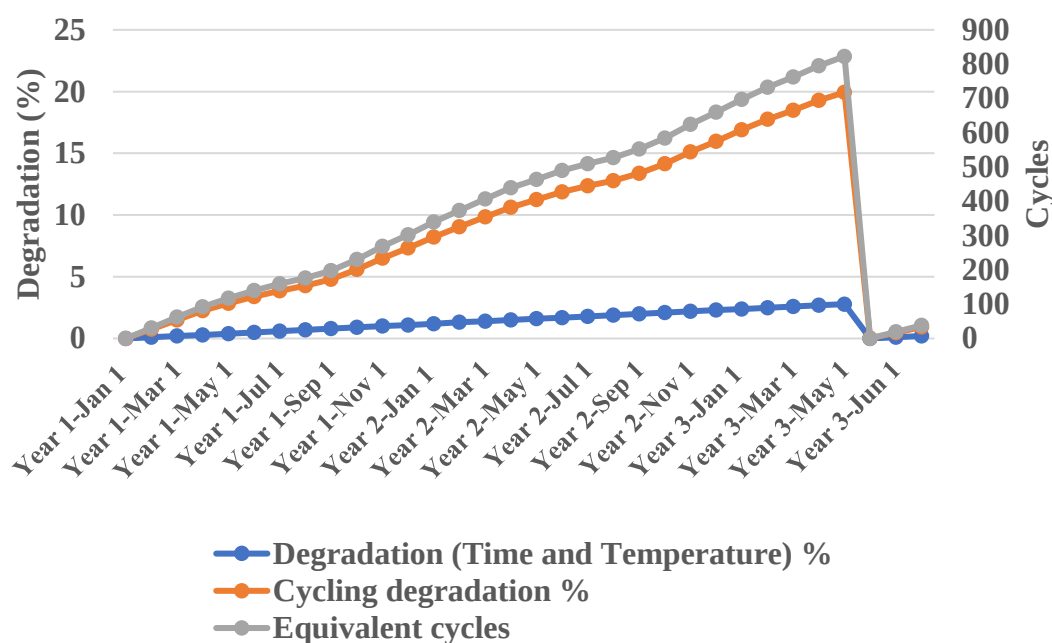


Figure 12. Degradation and equivalent cycles of the battery.

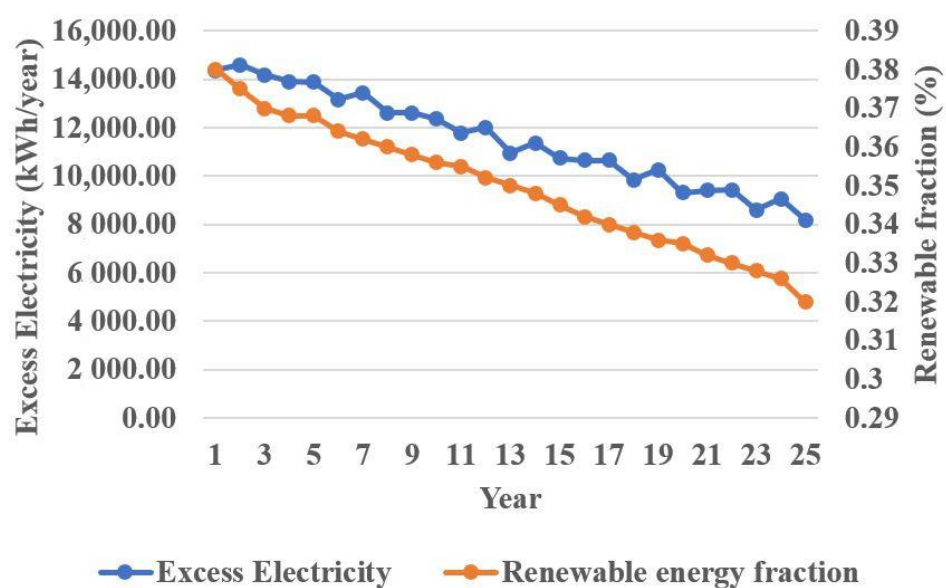


Figure 13. Comparison of excess electricity and RE fraction.

5.3. Sensitivity Analysis

There are a variety of reasons to run a sensitivity analysis with different values for a single input variable. In the design of RES, the sensitivity analysis is a tool that can show the importance of a particular variable and how the output changes depending on its value. If the system is highly sensitive to a particular variable, then the designer will have to spend more money and time to get accurate values of that parameter. A sensitivity study is carried out in this section to examine the impact of ambient temperature and wind speed on the system capabilities. One prominent factor influencing the PV performance is the temperature. It is well known that PV cell temperature and the ambient temperature are the same at night. During the day, however, the PV cell temperature exceeds the ambient temperature by about 30 °C or more due to the PV array's dark color, which consumes a lot of energy [21]. Since, Al-Jouf experiences high temperatures during most periods

of the year, so it is vital to investigate the behavior of the system with the changes in the ambient temperature. Consequently, the ambient temperature was varied from 36 °C to 45 °C. Figure 14 shows the ambient temperature on the 1st year multi-year PV output and the battery throughput. It is obvious that an increase in the ambient temperature decreases the PV output, although new techniques are now being developed to improve the PVs efficiency under such conditions. It can be seen that the PV output varies from 34,733 kWh/year to 33,270 kWh/year [44]. In addition, the battery throughput rises with an increase in the ambient temperature, clearly indicating more energy storage as the PV output decreases.

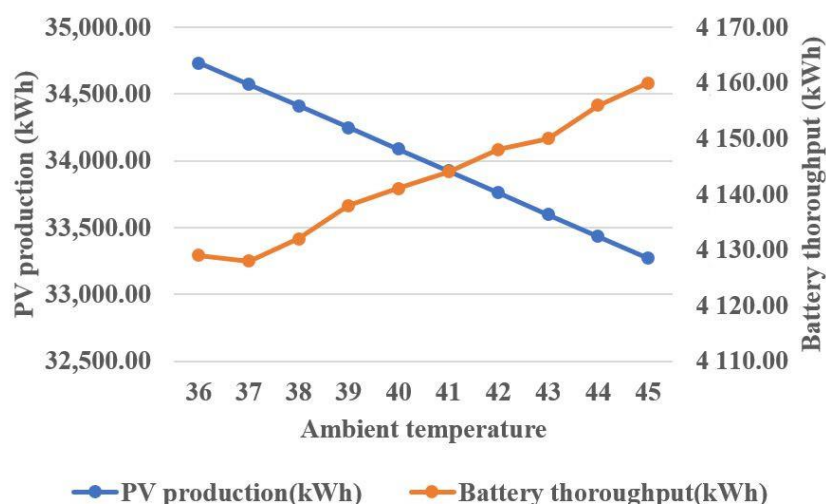


Figure 14. PV production and battery throughput with change in temperature.

To understand the impact on the system NPC and LCOE, a sensitivity analysis of ambient temperature variability is performed. From Figures 15 and 16, the NPC rises from USD205,733 to USD206,416, when the temperature varied from 36 °C to 45 °C. Similarly, there is a rise in the LCOE from 0.2022 to 0.2039. It is an indicator that in the design of a hybrid system with RES, ambient temperature may play an important role. Figure 17 shows the variability of the wind speed on the system LCOE. It is obvious that the LCOE decreases with an increase in the wind speed and the curve flattens after 12 m/s. For the case of Al-Jouf, the yearly average wind speed is 6.6 m/s, the variation of the wind speed will not have any serious impact on the system performance.

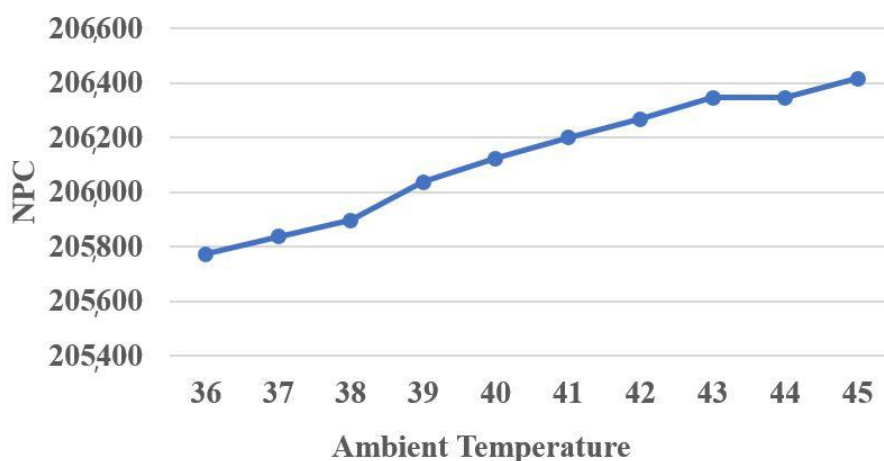


Figure 15. Variation of the NPC with the ambient temperature.

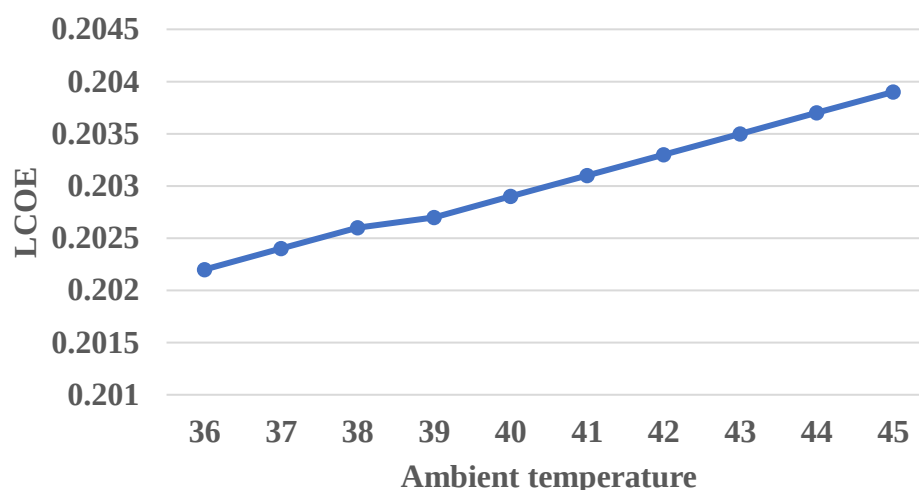


Figure 16. Variation of the LCOE with the ambient temperature.

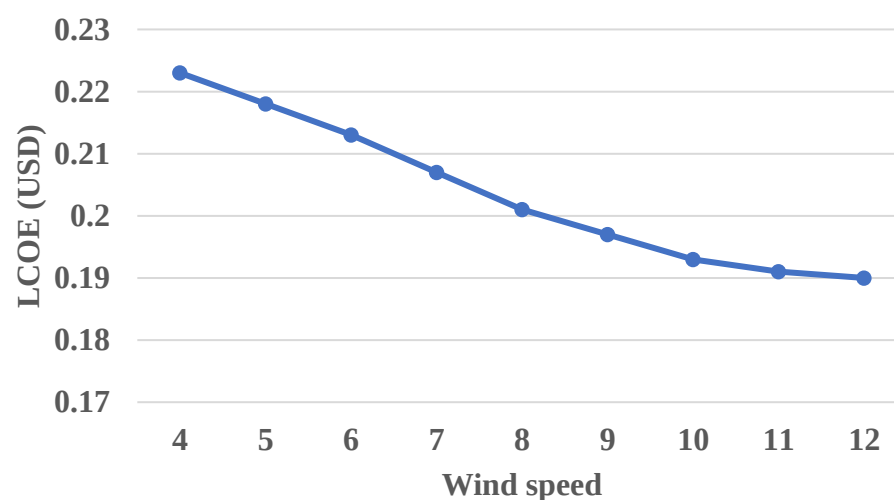


Figure 17. Variation of the LCOE with the wind speed.

6. Conclusions

For a remote location at Al-Jouf, Saudi Arabia, an optimal PV/wind/diesel/battery system has been designed. HOMER is used to design and simulate the system with a project lifetime of 25 years. Two scenarios were considered, one without the multi-year inputs and advanced storage modules while the other used the multi-year input and advanced storage modules. For the case without the multi-year module, the simulation results indicate that a combination of 24.5 kW PV, a 3 kW wind turbine, a 20 kW diesel generator, 12 battery strings and a 13 kW converter is the most feasible solution for this case study at USD191,943.9 NPC and USD0.2089 LCOE. For the case with the multi-year module and advanced storage system, the yearly load growth, yearly PV degradation, yearly battery degradation and yearly fuel price parameters have shown a significant impact on performance of the system. The diesel generator's power output rises by 38% over a span of 25 years, while the output of the PV generator drops by 11.3%. These results led to the increment of the fuel consumption, CO₂ emission and reduction of the battery throughput over the 25-year project time. As a further contribution of the paper, the ambient temperature was varied from 36 °C to 45 °C and its effect on the first year simulation results of the system evaluated. The PV production drops from by 4.2%, whereas the battery throughput rises showing the need for more energy storage. It is important to note that the rise in ambient temperature has also resulted in an increase in NPC and LCOE.

Since the KSA has already planned to install wind and PV power plants in many locations (Al-Jouf inclusive) across the kingdom by the year 2030, the results presented in this paper shows a more accurate evaluation considering realistic parameters that can have a huge impact on the system performance.

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