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Feasibility Analysis of PV/Diesel/Battery Hybrid Energy System Using Multi-year Module

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Abstract- Limited access to electricity in remote rural areas is one of the most challenging issues in Iraq. The utilization of renewable energy technologies for off-grid electricity generation has become an attractive option for minimizing the concerns of global warming and continuous depletion of fossil fuels. This work aims to study the techno-economic and environmental feasibility of using a PV/diesel/battery hybrid energy system to supply electricity for a remote rural village in Iraq. HOMER software is utilized to evaluate the optimization and the sensitivity analysis using a multi-input module by considering the effect of components degradation, load growth, and fuel price fluctuations on the performance of the system during the project lifetime. Results indicate that the most economical combination consists of a 12 kW PV, a diesel generator with a capacity of 20 kW, 15 batteries and a 6 kW power converter, at a net present cost of $ 162703. Moreover, the multi-year input variations have a considerable influence on system performance. The batteries show degradation of 24.2% by the end of their lifetime. Furthermore, among the project lifetime, PV production is reduced by 10% whilst diesel production is increased by 25.6% thereby increasing CO_2 emission by 23.1%. Likewise, the sensitivity analysis on ambient temperature demonstrates that the PV and batteries are highly affected by temperature increment, which increases the annual output energy of batteries from 5496 kWh to 5871 kWh whilst reducing the lifetime of batteries from 26.5 months to 23.5 months and the annual PV production from 18268 kWh to 17332 kWh, which generally affects the economic performance of the system negatively.

Keywords Rural areas, Solar, Diesel, Hybrid, Multi-year, Net present cost

1. Introduction

At present, most human energy demands are supplied by fossil fuel energy resources, including oil, gas and coal [1]. However, the burning of fossil fuel to generate electricity is the major source of greenhouse gas emissions which is the most serious driver of global warming and air pollution [2, 3]. By 2030, the CO_2 emission released from the fossil power generation system is expected to increase by 20% from the current global energy-related CO_2 emissions [4]. Meanwhile, the progressive increase in energy consumption along with the rapid depletion of conventional energy resources are other motivations for reducing fossil fuel dependence [5]. In this circumstance, renewable energy technologies can be the future of power generation because they are replenishable and environmentally friendly [6–8]. The world shows a considerable increment in the utilization of renewable energy resources in recent years. By the end of 2017, the generation of electricity from renewable resources was approximately 2195 GW, which provided approximately 26.5% of the global electricity. Figure 1 shows the estimated renewable energy share of global electricity production in 2017 [9].

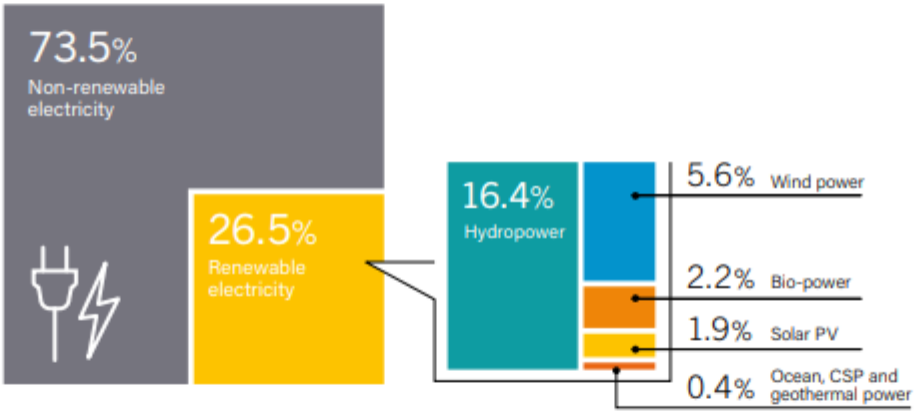

Fig. 1. Share of renewable energy sources by the end of 2017

Solar energy is a favored choice in electricity generation among various renewable energy sources that can be used in the decentralized electricity systems. It can provide a low-cost and reliable energy for rural areas. Moreover, being a green energy source with zero emissions increases its applicability [10]. Iraq is blessed with a huge amount of solar energy because it lies in earth-sun belt area. The amount of incoming radiation intensity varies from 416 $W/m^2/hr$ in January to 833 $W/m^2/hr$ in June. Most nations cannot compete with the high daily number of bright sunshine hours across Iraq. Moreover, the winter season in the country, which is usually cool, has more sunny days than snowy, rainy, cloudy and foggy days [11]. Table 1 presents the yearly solar radiation of various areas of Iraq [12]. The solar radiation in the southern and middle areas of the country is higher than that in the northern regions. However, up to the present time, the country has been suffering from acute electricity shortage. The electricity sector faces many challenges in all levels of energy production, including generation, transmission and distribution of electricity to consumers [13]. Electricity is available only for limited hours per day. Moreover, most of the remote rural places are undeveloped and face difficulties in terms of electricity access. Despite these problems and the high potency of solar energy resource, the current implementation of solar energy technology to produce electricity is incomparable to its potential. The absence of communication among government agencies, and between government and non-governmental organizations along with the lack of knowledge and awareness of renewable energy technologies limit the development of solar energy technology to the private sector and individual initiatives [14].

In contrast to fossil fuel systems, most renewable energy sources face the issue of being intermittent energy sources, depending on weather conditions, which negatively affects the production of energy. To overcome this issue, renewable energy sources can be integrated with other conventional sources and energy storage systems to provide energy supply in reliable ways [15–17]. This study presents a techno-economic and environmental feasibility study of a standalone PV/battery/diesel hybrid energy system (HES) to supply electricity for a remote rural area in Iraq.

Table 1. Annual solar radiation for different places of Iraq

Location	Annual solar radiation MJ/m^2
Baghdad	6997.46
Haditha	6662.75
Khanoqin	6556.3
Al-Rutbah	7114.44
Kirkuk	6660.17
Al-Mosul	6318.83
Sulaimaniya	6727.42
Al-Diwaniya	7021.23
Al-Basrah	6835.46
Al-Hai	7030.82
Al-Nasiriya	7263.97
Al-Samaua	7123.67
Al-Amara	7021.23
Al-Hai	7030.82
Zakho	6835.46

Feasibility analyses of HESs have been conducted in many previous studies. Yilmaz and Dincer [18] presented an optimal design of a PV/diesel/battery HES for a summer house in Turkey. The results showed that the optimum sizing of the proposed system proved to be very economical and environmental choice as an energy source for houses. The authors in [19] designed a stand-alone hybrid power system consisting of PV, diesel, and batteries as an alternative to the diesel system for a residential home in Nigeria. They concluded that although the capital cost of a PV/diesel/battery system is considerably higher than that of a diesel/battery system, the net present cost (NPC) is extremely lower than that of the generator and battery combination. The feasibility of an off-grid PV/diesel HES for a rural village in UAE was investigated in [20]. The results indicated that the stand-alone PV-diesel power system is more cost-effective than an extension to the grid. Moreover, the proposed system reduces CO_2 emission by 23% compared with the diesel-only system. In [21], three different HESs were compared to supply electricity for an off-grid remote village in South

Africa. The three systems are PV/diesel, PV/battery, and PV/diesel/battery. The optimal solution indicated that PV/diesel is the most reliable and economical system among the three systems. However, in previous studies, the analyses were conducted based on a single-year module, in which the simulation is performed only for a single year and then extrapolation is performed to calculate the economics over an entire project lifetime. Therefore, in a single year module, every year will be exactly like the first one. In this study, the simulation is implemented based on a multi-year module, in which the variations that occur over the project lifetime can be investigated. The simulation in a multi-year module is performed for every year in the project lifetime. Hence, some important phenomena can be modeled unlike in a single-year module. In the current work, the considered phenomena are as follows:

- PV degradation: Degradation is the most crucial factor in the evaluating the long-term behavior of solar modules and assessing its reliability. The PV degradation is known as the progressive retrogression in the thermal and electrical characteristics of a PV cell/module/array/system with various mechanisms and factors at each level. In all cases, the main exterior factors related to the degradation in the operation field are temperature, snow, dust, precipitation, and humidity. At the array level, the mentioned factors along with module mismatches and shading effect contribute in the degradation. These factors lead to different degradation mechanisms and cause considerable stress during a PV system lifetime [22, 23]. Usually, the warranties on PV modules during the first 5–10 years are between 90%–95% of the peak power, increasing to 80%–87% for approximately 25 years [24].

- Battery degradation: Understanding the battery degradation mechanisms is important for predicting the battery lifetime during its operation within an application. Batteries are exposed to natural degradation over time regardless of the charge-discharge cycles. However, batteries are also faced with degradation that comes from cyclic charging and discharging. The battery life related to natural degradation is called calendar life, whereas the one caused by the effect of charge–discharge cycles is referred to as cycle life [25, 26].

- Diesel price fluctuation: Significant variations in fuel prices are a popular event. Various factors play vital roles in fuel price fluctuation. Such fluctuation has drawn attention to the utilization of renewable energy sources that can aid stabilize the overall energy prices [27].

- Load growth: Increment or decrement may occur in load demand during the project lifetime. The effect of load change on the performance of the system for the entire project lifetime is considered in the multi-year module.

2. Materials and Methods

2.1. Specification and Load Profile of the Selected Site

The economy of rural areas is based on agriculture, and thus the people usually spend most of the time outside their homes during the day for work. At night time, an increment in load demand can be observed. In this study, Budjah, a small remote village located in Diyala, Iraq, is selected as a case study. Figure 2 presents the load profile of the village, showing the variance throughout 24 hours of a day [28]. The electric load profile is performed carefully by considering the load requirements of the residential unit. Like most remote villages, the load demands are small which are required to satisfy the electrical appliances and lighting. The average daily energy demand is estimated to be 145 kWh/day, with a daily average 6.04 kW and a power peak load of 14.9 kW.

2.2. Solar Radiation and Ambient Temperature

The output power of PV mainly depends on solar radiation and ambient temperature. HOMER software handles these two parameters as input variables. The expression between the output power and these parameters will be explained in Subsection 2.4. The solar radiation and ambient temperature data are detailed as follows:

- Figure 3 shows the data of solar radiation and clearance index for the location (33° N latitude and 44° E longitude) that are obtained from NASA’s website [29]. The monthly solar radiation data for the selected site vary between 2.62 kWh/m^2/day in December and 7.56 kWh/m^2/day in June, with an annual average of 5.02 kWh/m^2/day. The area obviously has a massive solar potential and can be an attractive choice for efficient electricity generation through PV panels.

- The performance of PV panels is highly dependent on ambient temperature. Figure 4 shows the monthly average ambient. The average annual temperature is 23.56 °C, with high temperature during the summer season from May to September and low temperature in winter. The highest ambient temperature is recorded in July at 36.15 °C, whereas January is found to be the coldest month with an ambient temperature of 9.77 °C.

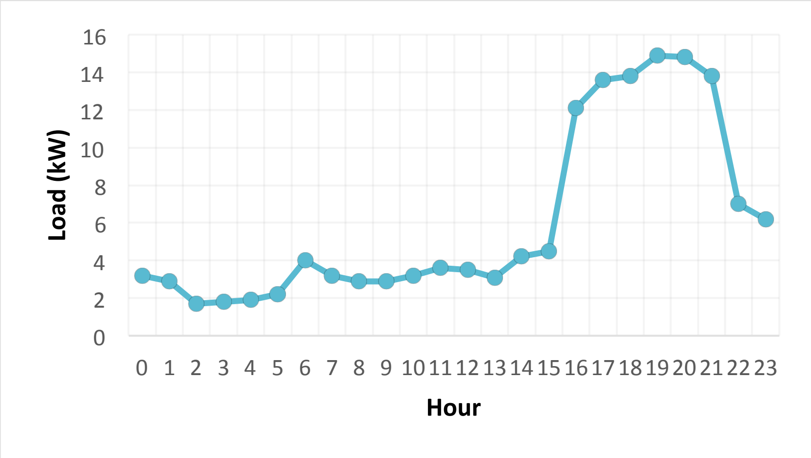

Fig. 2. Daily electric load profile of the selected residential unit

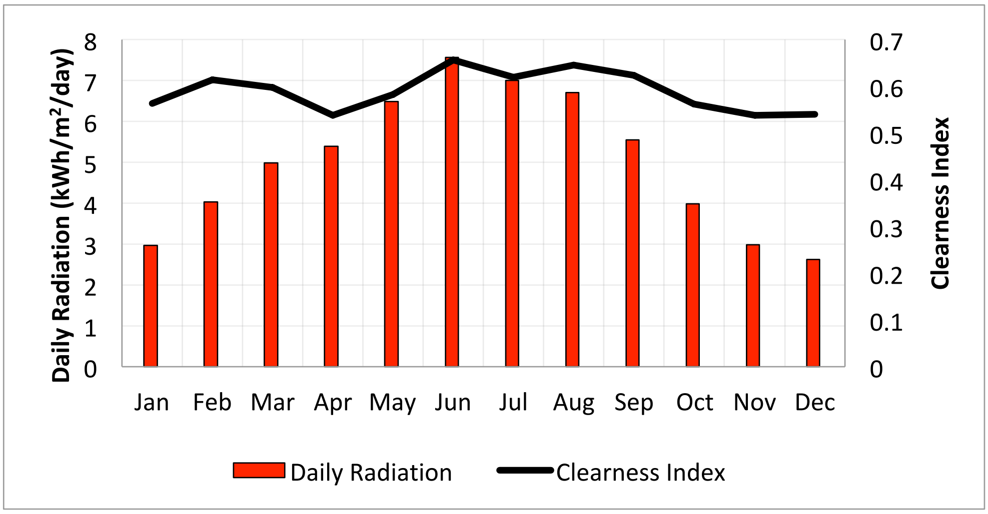

Fig. 3. Monthly average global horizontal radiation and clearance index of the studied location

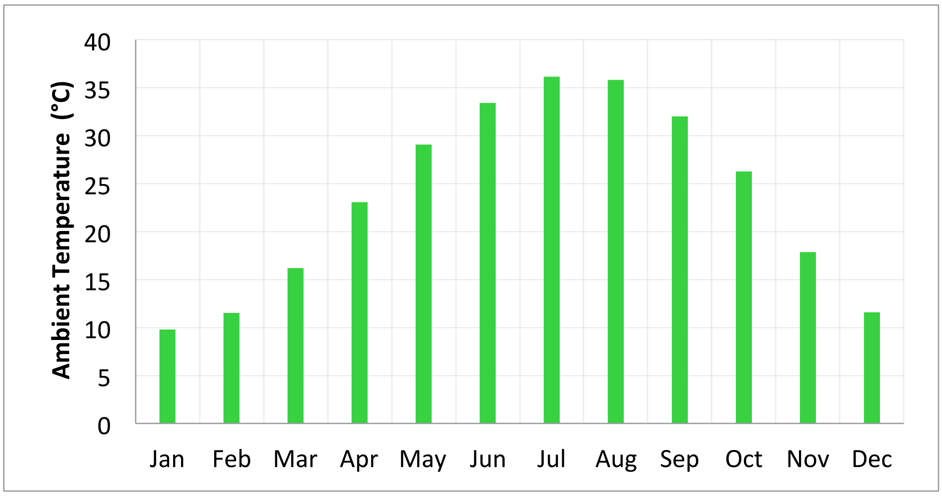

Fig. 4. Monthly average ambient temperature of the studied location

2.3. System Components

The proposed HES in this study consists of four components, namely, a PV system, a diesel generator, a converter, and batteries, where cycle charging is selected as the dispatch strategy in this simulation in which whenever a generator is required to supply the load, it works at full output power. Surplus electrical production charges the battery. Figure 5 shows the designed configuration of the PV/diesel/battery HES. Table 2 presents the techno-economic input parameters for all components. The technical parameters and costs of the components are taken from different references [14, 30–32].

2.4. Mathematical Modeling of Proposed HES

2.4.1. PV Output Power

The following equation is used in HOMER to compute the total electric power produced by PV [33, 34]:

$$P_{PV} = Y_{PV} f_{PV}\left(\frac{\bar{G}_T}{\bar{G}_{T,STC}}\right)\left[1+\alpha_p(T_c - T_{c,STC})\right] \quad (1)$$

where Y_{PV} is the PV rated capacity under standard test conditions (kW), f_{PV} is the de-rating factor of PV, $\bar{G}_T$ is the episode of the solar irradiation on the PV panels in the current time step (kW/m^2), $\bar{G}_{T,STC}$ is the incident irradiance at standard test condition (1 kW/m^2), α_P is the temperature coefficient of power (%/°C), T_C is the temperature of the PV cell (°C) in the current time step and $T_{C,STC}$ is the temperature of PC cell under standard test conditions (25 °C).

2.4.2. Economic Model

The purpose of HOMER is to reduce the costs in operating the system and determining the optimum system configuration, wherein economics plays a crucial role in the simulation. The optimum combination of HES components is obtained based on the NPC, which is the sum of all costs and revenues throughout the project lifetime. The total NPC of a system is calculated as follows [20, 35, 36]:

$$NPC = \frac{TAC}{CRF(i,T_p)} \quad (2)$$

where TAC is the total annualized cost, i is the annual real interest rate (%), T_p is the project lifetime (year) and CRF is the capital recovery factor that is given by [20, 35, 36]:

$$CRF(i,n) = \frac{i\,(1+i)^n}{(1+i)^n - 1} \quad (3)$$

where n is the number of years.

Salvage cost is the projected resale value of an asset at the end of its useful life. It is considered in the calculation of NPC and calculated as [31, 36]:

$$SC = C_{RC}\frac{T_{rem}}{T_{com}} \quad (4)$$

where C_{RC} is the cost of replacement ($]), T_{rem} represents the remaining life of the component (year) and T_{com} refers to the component lifetime (year).

Cost of energy (COE) is the average cost per kWh of producing electricity, and is obtained as [36, 37]:

$$COE = \frac{C_{tot}}{E_{tot}} \quad (5)$$

where E_{tot} is the total electrical load served (kWh/yr).

2.5. Multi-year Inputs

To model the parameters changes that occur over the project lifetime, a constant percentage is set by which a component can change every year. PV degradation, diesel price fluctuation, and load growth are 0.5%/year, 1%/year, and 1%/year, respectively. Moreover, battery degradation is modeled automatically.

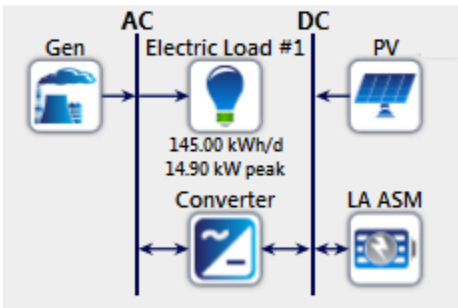

Fig. 5. Configuration of PV/diesel/battery HES

Table 2. Specification of components and their corresponding costs

Description	Specification
• **PV system**	
Tracking system	Fixed
Nominal operating cell temperature	47 °C
Temperature coefficient	− 0.5% / °C
Efficiency at standard test condition	13%
De-rating factor	80%
Capital cost	$ 1500/kW
Operating and maintenance cost	$ 1000/kW
Cost of replacement	$ 5/kW/year
Lifetime	20 years
• **Diesel generator**	
Cost of capital	$500/kW
Cost of replacement	$ 400/kW
Cost of operating and maintenance	$ 0.02/kW/hr
Lifetime	15000 hr
• **Batteries**	
Model	Lead acid [ASM]
Nominal capacity	1.03 kWh
Nominal voltage	2 V
Capital cost	$ 300
Replacement cost	$ 300
Operating and maintenance cost	$ 10 /year
• **Converter**	
Efficiency	90% for inverter, 85% for rectifier
Cost of capital	$550/kW
Cost of replacement	$ 450/kW
Cost of operating and maintenance	$ 5 /kW/year
Lifetime	15 years

3. Simulation and Results

The simulation results are presented and analyzed in this section. The technical feasibility is assessed to investigate the possibility of supplying electricity from the HES to meet the load throughout the year. Moreover, the economic forecasts and environmental impacts of the system are discussed in detail. Furthermore, to investigate the effect of the variation of ambient temperature on system performance, sensitivity analysis is conducted by varying the temperature between 18 °C and 27 °C. The simulation is performed with a project lifetime of 20 years at an annual real discount rate of 7.8 % and annual maximum capacity shortage of 1%.

3.1. Optimization Results Based on NPC

The feasible system is one that has the ability to deliver the power and satisfy the annual electricity demand. In HOMER, many different system configurations are simulated. The infeasible combinations (systems that do not meet the user-specified constraints) are eliminated and are not displayed in the optimization results whereas the feasible ones are sorted based on their NPCs. The simulation results indicate that the combination of components, which consists of a 12 kW PV, 15 batteries, a 20 kW diesel generator, and a 6 kW power converter, is the most optimal solution at an NPC of $ 162703 and a COE of 0.288 $/kWh. Figure 6 shows the cost summary of the proposed system. The details of the cost analysis are as follows:

- The proposed system has a capital cost of $ 35800. The contributions of the components for the capital cost are 50.28%, 27.9%, 12.6% and 9.22% for the PV, diesel generator, converter and battery, respectively.
- After the installation of the system, the diesel generator contributes 87.66% to the total O&M cost, whereas O&M costs of PV and batteries are extremely low. The total O&M cost of the system is calculated to be $ 19334.21.
- The total replacement cost of the system is $ 41705.57. This value comes from the summation of the replacement costs from diesel generator, batteries, and the converter replacement costs. The PV does not need

replacement because its lifetime is 20 years, which is the same as the project lifetime.

- The PV, batteries, and converter do not consume any fuel. Therefore, the diesel generator is responsible for the total fuel cost, which is estimated to be $ 67429.96.
- The remaining life of the batteries, converter and diesel generator make the system has a salvage cost of $ –1566.48.

3.2. Energy Balance of the Optimized System

A small duration of approximately three days in July is selected to verify the energy share of the optimized system. The energy balance between different components of the system and the battery state of charge (SOC) of the selected period is shown in Fig. 7. At day time, the PV feeds the load and charges the batteries, whereas the generator remains off most of the time. The generator works to supply the load during the night hours with high load. During the last hours of the night in which the load demand is low, the load is satisfied by the batteries or generator alone. In the early sunshine hours, the batteries discharge the power to help the PV meet the load. Meanwhile, the PV and generator work to satisfy the load during the last day light hours. Furthermore, SOC is consistently above 50%, which is good because excessive discharge for a long period damages the batteries.

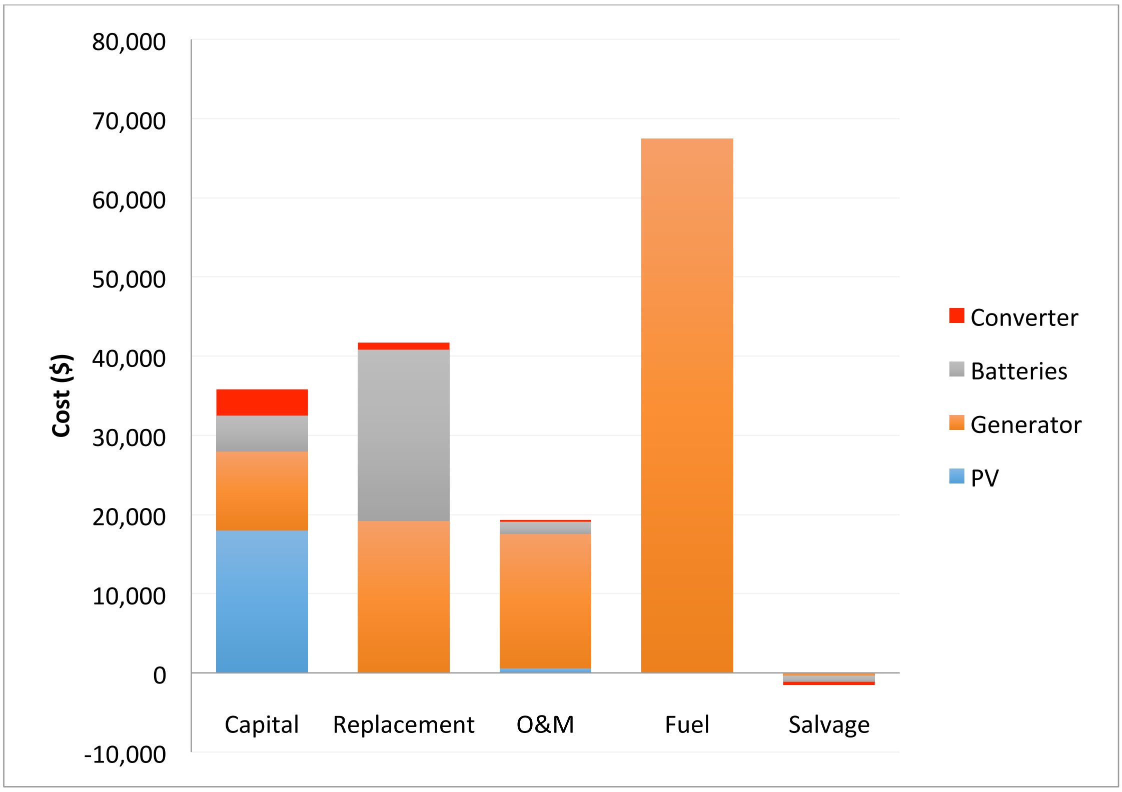

Fig. 6. Cost summary of PV/diesel/battery HES

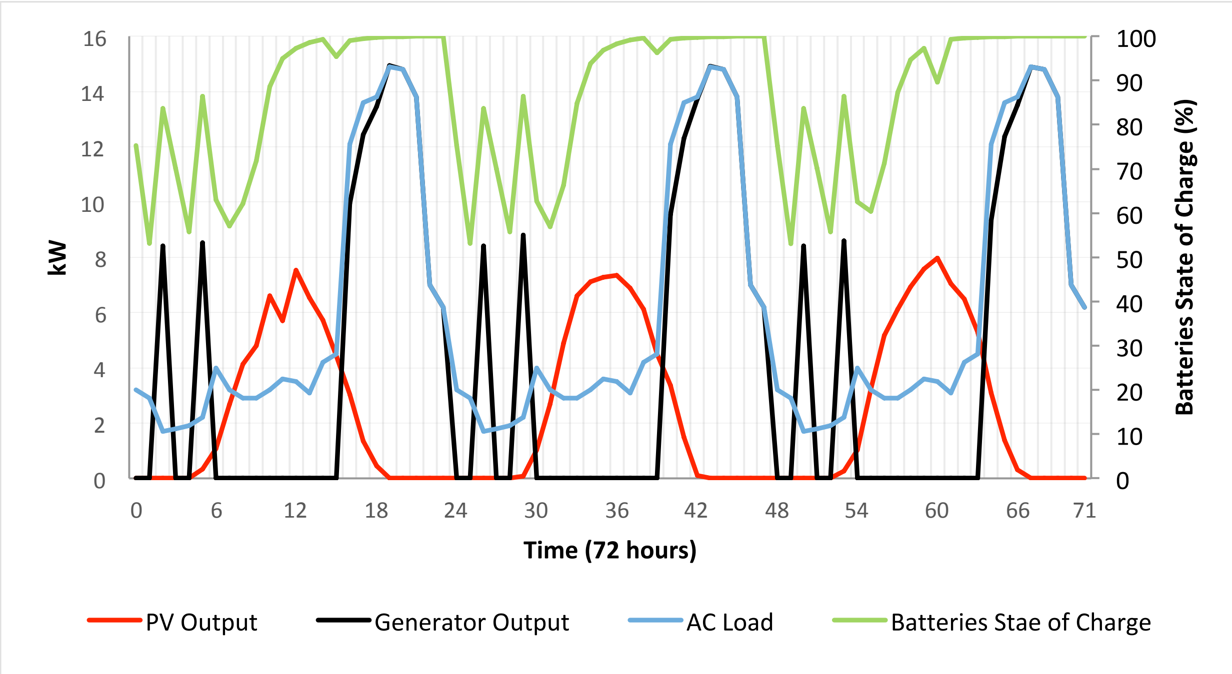

Fig. 7. Energy balance and battery SOC of PV/diesel/battery HES

3.3. Effect of Multi-year Module on the System Components

This subsection discusses the effect of the multi-year module on the performance of the system. Figure 8 shows the effect of the multi-year module on the PV and diesel production, CO_2 emission, battery losses, and total load served. Over the entire project lifetime the degradation of the components has a significant effect on the system. However, during the 20 years, the PV production decreases from 17689.55 kWh/year to 10682.56 kWh/year, whereas diesel generator increases from 43415.04 kWh/year to 54551.46 kWh/year. The increment of diesel generator utilization increases the CO_2 emission from 38012.24 kg/year to 46795.38 kg/year. Meanwhile, the load growth increases the total load served from 52923 kWh/year to 63926.49 kWh/year. Moreover, the output energy of the batteries shows many fluctuations over the project lifetime because of the storage depletion and the replacement of batteries from time to time.

Further details on the types of battery degradation are provided in this part. The modified kinetic battery model is selected in this study. It experiences two types of degradation over its lifetime. The first degradation is related to the wear from cycles adjusted for depth of discharge. In other words, it tracks the cycle fatigue on the battery and therefore also called cycling degradation. The second degradation is associated with the time and temperature over the battery lifetime. Whether the battery is idle or being used, the degradation of the storage component increases with each time step. The increment rate only depends on the temperature [38]. The battery calendar and cycling degradation along with the equivalent cycles for the entire project lifetime are presented in Fig. 9. The result shows that cycling degradation contributes the most to the total degradation with approximately 20% by the end of the battery life time. Meanwhile, calendar degradation is only approximately 4.22% for this period. Furthermore, the batteries need to be replaced after 825 equivalent cycles.

3.4. Sensitivity Analysis of Ambient Temperature

In this subsection, a sensitivity analysis is performed to investigate the effect of ambient temperature on the performance of the system. The ambient temperature is varied between 18 °C and 27 °C to investigate its effect on the performance of the batteries and PV. Figure 10 presents the effect of temperature on the first-year output energy of the batteries and their throughput along with the battery lifetime. The output energy of batteries increases from 5496 kWh to 5871 kWh when the ambient temperature increases from 18 °C to 27 °C. Moreover, this increment causes the batteries throughput to increase from 6154 kWh to 6579 kWh which reduces the batteries lifetime from 26.5 months to 23.5 months. These results support the fact that raising the temperature increases the chemical reactions in the battery and therefore a better capacity can be achieved. However, this phenomenon also reduces the battery lifetime because of unwanted chemical reactions [39, 40].

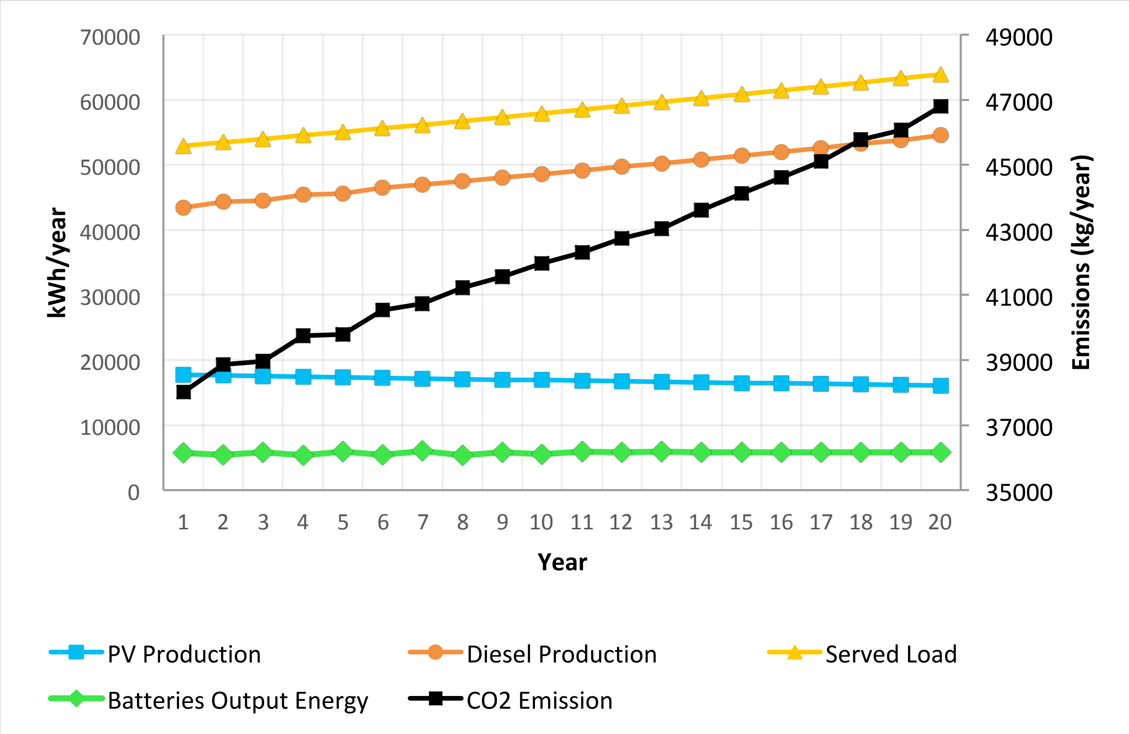

Fig. 8. System behavior under multi-year module

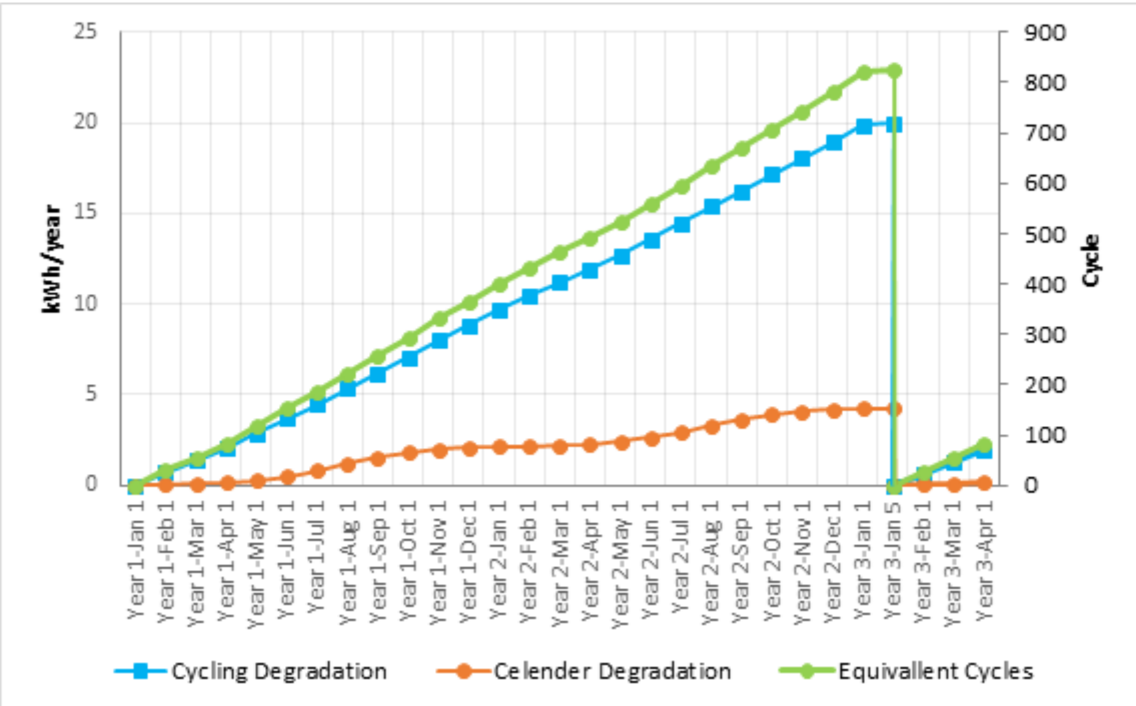

Fig. 9. Degradation and equivalent cycles of the battery

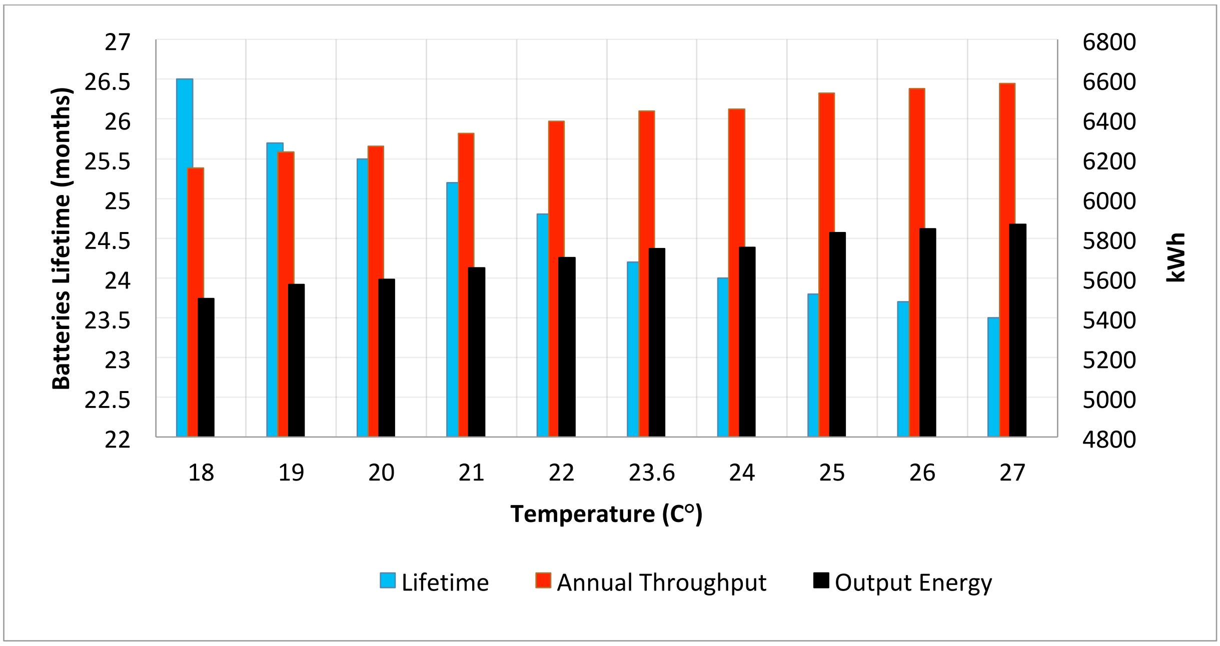

Fig. 10. Influence of ambient temperature on batteries performance

The minimum SOC is the SOC below which the battery must not be discharged, given a percentage of the total capacity. Most rechargeable batteries are never truly fully discharged to prevent damaging the battery due to excessive discharge. The minimum SOC in the range of 30%–50% is generally recommended. The effect of temperature on the system performance in terms of SOC dependence is also obtained in this part. As shown in Fig. 11, low output energy, battery throughput and high lifetime are achieved with the increasing minimum SOC. Furthermore, the effect of temperature becomes more effective at high minimum SOC. At 20% minimum SOC, increasing the temperature from 18 °C to 27 °C increases the output energy and throughput by approximately 2.1% and the by approximately 2.6%. Meanwhile, by setting the minimum SOC to 50% with the same temperature variation, the output energy and annual throughput show an increment of around 13.95% and 12.72% respectively, whereas the lifetime decreases by approximately 13.25%.

Temperature is one of the most remarkable environmental factors that affect the efficiency of PV. At night time, the ambient temperature and PV cell temperature are the same. However, through the full-sun period, the PV cell temperature exceeds the ambient temperature by 30 °C or more because the PV array is usually has a dark color which absorbs a high amount of solar energy [35]. The output power of the PV is known to decrease with increasing cell temperature. Figure 12 presents the effect of temperature variation on the first-year PV production of the proposed system. The PV production decreases from 18268 kWh to 17332 kWh when the temperature increases from 18 °C from 27°C. However, increasing the efficiency of PV by reducing the cell temperature using different cooling methods has become an interest [41–43].

To investigate the effect of temperature on the system from the economic prospective, the sensitivity analysis of the temperature variation is also conducted to obtain its effect on the NPC of the system. The effect of the ambient temperature on the NPC is presented in Fig 13. The result depicts that the NPC shows an increment from $161932 to $163148 when the ambient temperature increases from 18 °C to 27 °C.

4. Conclusion

The utilization of HESs is an efficient, reliable and cost-effective option for electricity generation in off-grid locations. The present work examines the techno- economic and environmental feasibility analysis of a PV/diesel/battery HES to supply electricity for a remote rural village in Diyala, Iraq. HOMER software is used for optimization and simulation of the system with a projection period of 25 years using a multi-year module to investigate how the outputs vary over the years of the project lifetime. The simulation results indicate that the combination of 12 kW PV, a diesel generator with a capacity of 20 kW, 15 batteries, and a 6 kW power converter is the optimal solution for this case study at an NPC of $ 162703. Over the project lifetime, PV and degradations, load growth and fuel price escalation are found to have considerable effects on energy share and environmental performance. By the end of the project lifetime, PV production decreases from 17689.55 kWh/year to 10682.56 kWh/year, whereas diesel generation increases from 43415.04 kWh/year to 54551.46 kWh/year. Moreover, the degradation of batteries reaches approximately 24.2% by the end of their lifetime. All these results tend to reduce the renewable penetration and increase the utilization of diesel generator, thereby increasing the CO_2 emission from 38012.24 kg/year to 46795.38 kg/year. Furthermore, the variation of ambient temperature from 18 °C to 27°C increases the battery output energy of the first year from 5496 kWh to 5871 kWh but reduces the lifetime from 26.5 months to 23.5 months and the first-year PV production from 18268 kWh to 17332 kWh, thereby increasing the NPC by 0.75%. Generally, the outcomes achieved from this study can be considered as an initial step to encourage dependence on renewable energy systems for electricity production.

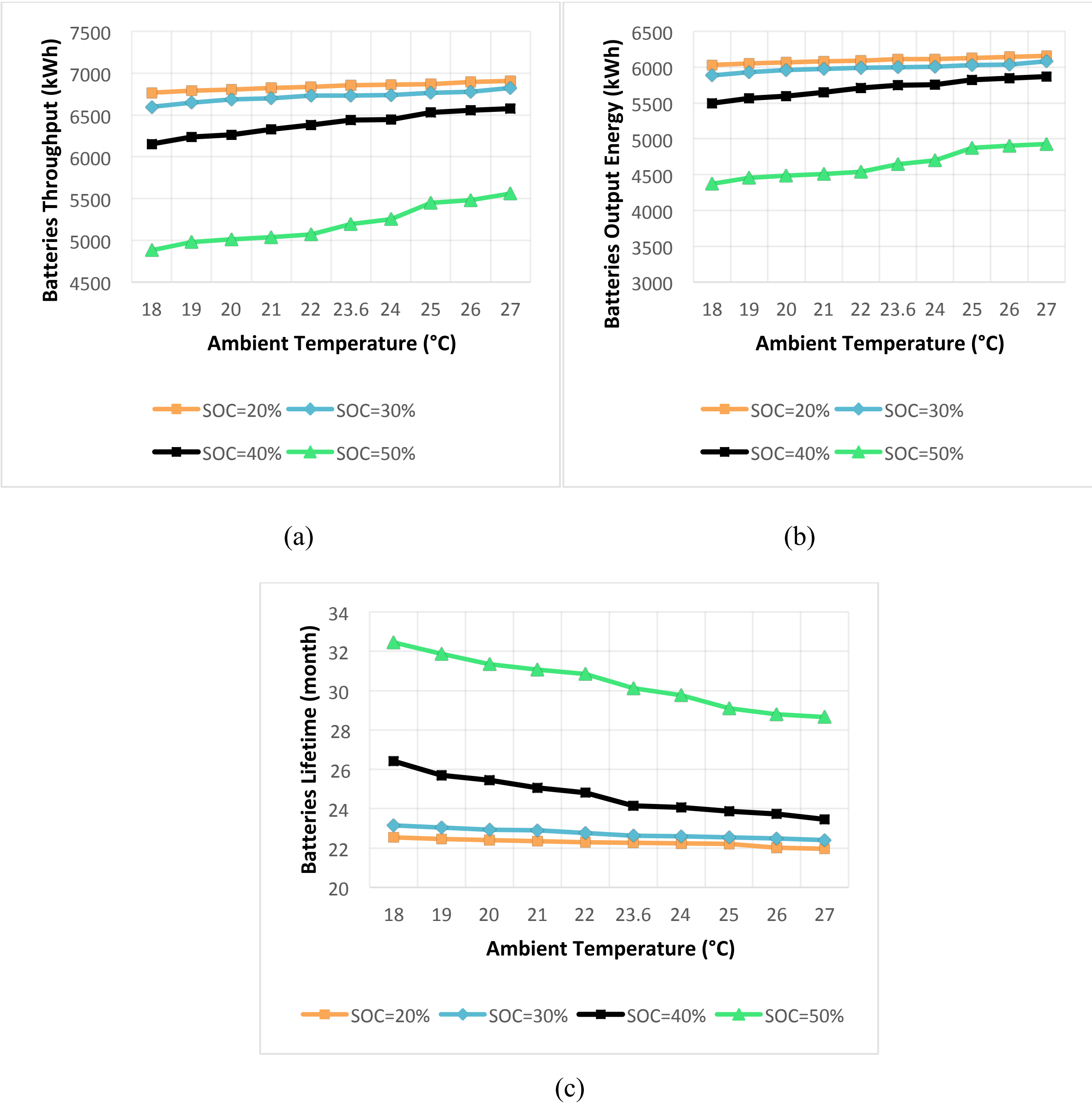

Fig. 11. Influence of ambient temperature on (a) batteries throughput, (b) batteries output energy and (c) batteries lifetime in SOC dependence

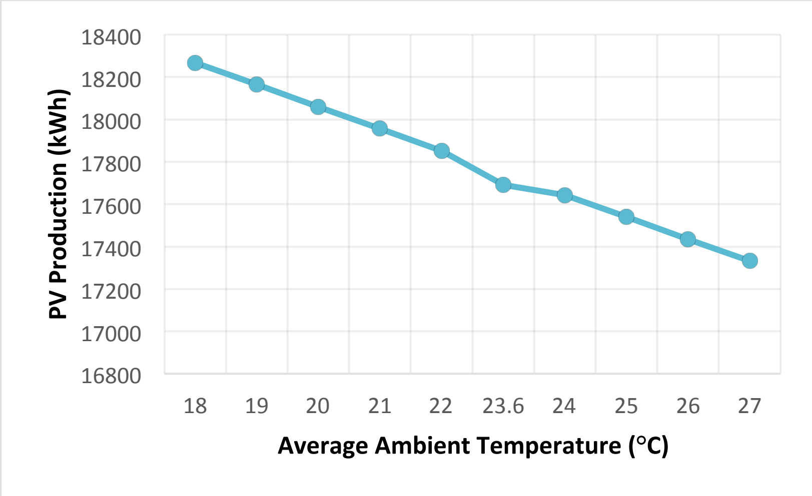

Fig. 12. Influence of ambient temperature on PV production

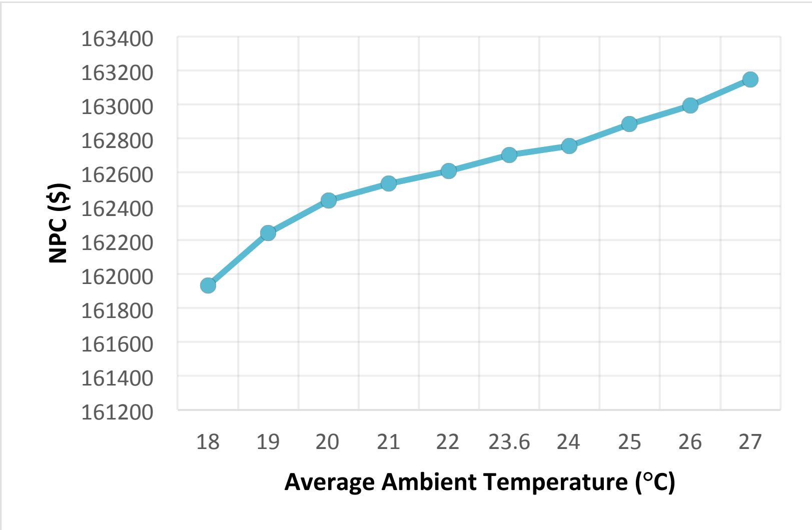

Fig. 13. Influence of ambient temperature on NPC

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