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Techno-Economic analysis of Hybrid Renewable Energy Systems for Remote Areas

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Abstract

Renewable energy technology has experienced a comprehensive development throughout the world as its presence could be economically and environmentally feasible. Therefore, sustainable energy development is an opportunity to encourage economic growth and preserve the environment using clean, safe, and more affordable energy. Degradation of the environmental resources is among the biggest challenges, whilst the conventional energy sources are the most contributors. Siwa Oasis in Egypt suffers an environmental crisis where its power plant is diesel generator based, which produces more than 26,000 tons of CO_2 per year, as well as the configuration is cost ineffective. These negative issues should be eliminated by utilizing a Hybrid Renewable Energy System (HRES) that achieving techno-economic feasibility and environmental sustainability. This paper will discuss the technical analysis and the economics of the proposed HRES in Siwa Oasis, this could be a helpful guideline for the decision makers to implement an economic feasible and sustainable configuration for remote areas. Through a data collection method, detailed information of the electrical condition in Siwa Oasis are collected. These collected data employed to techno-economically analyze the required system using HOMER Pro. Two main scenarios have been evaluated for Siwa Oasis case, a HRES including the reliable existing diesel generators as a first scenario, while the second scenario is a HRES excluding these existing diesel generators. The optimum results revealed that the HRES including the existing diesel generator approved its cost-effectiveness with a Levelized Cost of Energy (LCOE) of o.0881 \$/kWh instead of 0.1886 \$/kWh for the second scenario.

Keywords: Hybrid Renewable Energy Systems, LCOE, Siwa Oasis.

1. Introduction

Integration between conventional and renewable sources making an electric energy system called Hybrid Renewable Energy Sources (HRES), working as a grid-connected or standalone system. Usually, the system consists of a renewable generator such as PV energy and wind energy, non-renewable generator such as diesel generators, power conditioning unit, storage, and sometimes a grid. The system can be composed of completely renewable sources when replacing diesel generators with a large storage (Ammari, Hamouda & Makhloufi, 2018).

Comparing with the single source systems, HRES presents a better option in terms of efficiency, cost, and reliability. Different combinations of hybrid systems can meet the basic requirements of power in non-electrified areas which suffered a lack of electricity. The unpredictable climate conditions directly affect the power generation from renewable-based Systems making a complex task for the design and operation of HRES (Vergara, Rey, Silva & Ordóñez, 2016).

A standard design composition of stand-alone hybrid energy systems is solar PV modules, wind turbines, batteries, DC/DC converters, Inverters, and other control devices. Optimal selection of hybrid systems depends on the decision variables such as PV panels or wind turbines number and the capacity of battery bank. A minimization of annual total cost would result by sizing of these components and optimal selection and therefore give better economical solutions. Generally, the load demand must be satisfied by available solar and wind energy resources (Aiad, Al-Shihabi & Badran, 2013).

Aberilla, Gallego-Schmid, Stamford & Azapagic (2020) in their study explained that for rural electrification, off-grid renewable energy systems are being increasingly installed commonly as community micro grids and stand-alone home systems. For remote communities, the sustainability of a certain option is not clear due to the availability of various technologies and configurations. For both home and community installations, various combinations and configurations were designed as a stand-alone hybrid renewable energy system of solar, wind, diesel generators, and battery storage. 15 micro-grids and 6 home systems were optimized and designed. The 21 configurations have been conducted to be designed and optimized for rural communities in Philippines. For each option, using HOMER Pro, the configurations were designed. The lowest environmental impact was achieved by PV panels, wind turbines and lead acid battery hybrid system for community micro grid options. On the other hand, for a home energy system, 88% of the impacts were caused by batteries, which had a major environmental hotspot.

Mousavi, Zarchi, Astaraei, Ghasempour & Khaninezhad (2021) presented in their paper a powerful investigation and useful reference for exploring the hybrid renewable energy systems feasibility for rural electrification. However, for different countries and locations, the feasibility study could be applied with different economical values and the potential of employing renewable energy sources can be studied. The researchers in their paper aimed to produce the feasible and appropriate solutions for different climate zones of remote areas. Moreover, their research is essential for decision makers to compare between grid extension and the hybrid renewable energy systems utilization. Hence, HOMER Pro employed to simulate various energy configurations. The results showed that the off-grid system is the most efficient solution for all selected villages. The grid extension Scenario is not recommended as the Net Present Cost (NPC) increased and the extensive CO_2 emissions rate produced with approximate 105 kg/year for the selected villages. A reduction in CO_2 emissions of 10000-2000 and 10-19% of energy losses will be achieved through utilizing the stand-alone system instead of grid extension.

Akram et al. (2020) in a research explained that due to the raised conventional fuels prices and renewable energy technologies improvement, remote areas could be supplied with electricity through a HRES which are commonly utilized as a stand-alone power system. Therefore, a specific daily load profile in a remote area can be met through optimizing a HRES. The design optimization of the HRES has been done utilizing HOMER Pro Software. The performance of the proposed design scheme was evaluated using four cases through HOMER Pro software. According to the results, the proposed design proved its suitability for remote areas. Additionally, the demand management with an efficient hybrid energy system will reduce carbon emissions as the system is efficient, as well as the reduction of overall system cost.

Budes et al. (2020) clarified that to ensure energy supply and fill the gap resulted from reliability problems in the Colombia Caribbean Region electrical sector, several thermo-electric plants are required. Hence, a HRES is proposed. The proposed system could meet a portion of the energy demand besides the reduction in the traditional energy sources environmental impact. The combination of the hybrid energy system is PV technology and wind turbine technology, works connected with the grid. Through HOMER Pro software, the optimal combination for a hybrid system obtained with 3 wind turbines and 441 PV panels. The resulted NPC of this system was $11.8 million and low CO_2 emissions of 244.1 tons per year.

saheb Koussa & Koussa (2016) illustrated that the growing energy consumption has led to serious environmental concerns have been raised due to the excessive use of fossil fuels. About 21.3 billion tons of CO2 is emitted per year due to fossil fuels burning to produce Energy. Meanwhile, deploying renewable energy generation promises a reduction in global CO2 emissions. The researchers in this study investigated the operations of a large-scale 67 MWh/day on-grid renewable energy system. Based on the economic and environmental impact, the study performed a comparison between a standard grid operation and a grid-connected renewable energy system.

According to Koussa's study, the economic indicators of NPC, LCOE and Payback Period were calculated using HOMER software that is a utilized to simulate a HRES in hot and arid climate regions of Salah and Adrar in Algeria. The results of the study revealed a high reduction in the LCOE with 81% and 76%, whereas 30% and 35% reduction in GHG emissions for the two regions respectively with the proposed grid-Connected renewable energy system.

2. Methodology

The scope of this study is to develop a solution for the interruption of electricity in Siwa Oasis, which is a remarkable problem, as well as the emitted pollution from the used diesel generators to produce electricity are economically infeasible and horribly harming the environment. The economic perspective is taken into consideration as there is a need to provide affordable solutions. Furthermore, performing the proposed project will help in providing jobs for the first nations of Siwa Oasis. The potential of implementation of renewable energy power plant in remote area has been Identified. Therefore, Collecting the required data for the techno-economic analysis is essential. The collected data has been utilized in HOMER Pro tool to compare proposed HRES scenarios.

3. Case Study

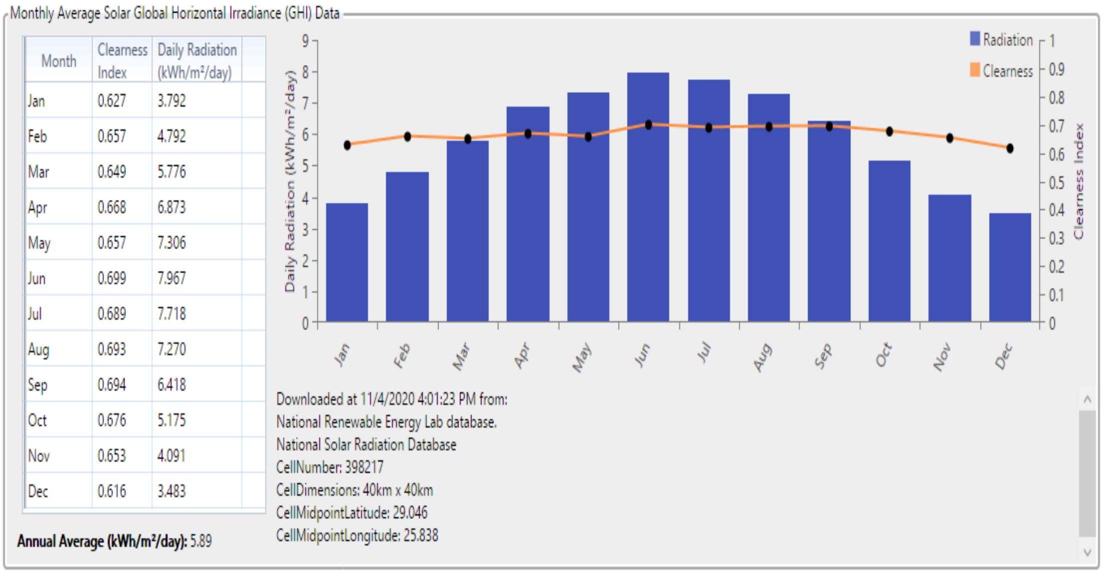
3.1. Weather Date

Siwa Oasis climate is classified as tropical and subtropical desert climate (BWh) according to Köppen-Geiger classification (2007). 21.3 °C is the average temperature in Siwa Oasis. The hot period lasts for about 4 months, from final third of May to the final third of September approximately, and the daily average high temperature cold reach more than 34°C. the hottest day in the year occurs in late July, when the high temperature is 38°C and the low temperature is 23°C. For about 3 months, the cool season occurs from late November to early March approximately, while the daily average temperature is 22°C maximum. January 29 is the coldest day in the year, while the average low of 6°C and high of 18°C (Weather Spark, 2018).

3.2. Solar Irradiance Data

According to the World Bank Group (2021), the Global Horizontal Irradiation (GHI) in Siwa Oasis is 2132 kWh/m2 per year, and the specific photovoltaic power output (PVOUT) is 1844 kWh/kWp. The monthly average solar irradiance can be seen in Fig. 1.

Figure 1. Monthly Average Solar Global Horizontal Irradiance Data in Siwa Oasis.



3.3. Cost Variables

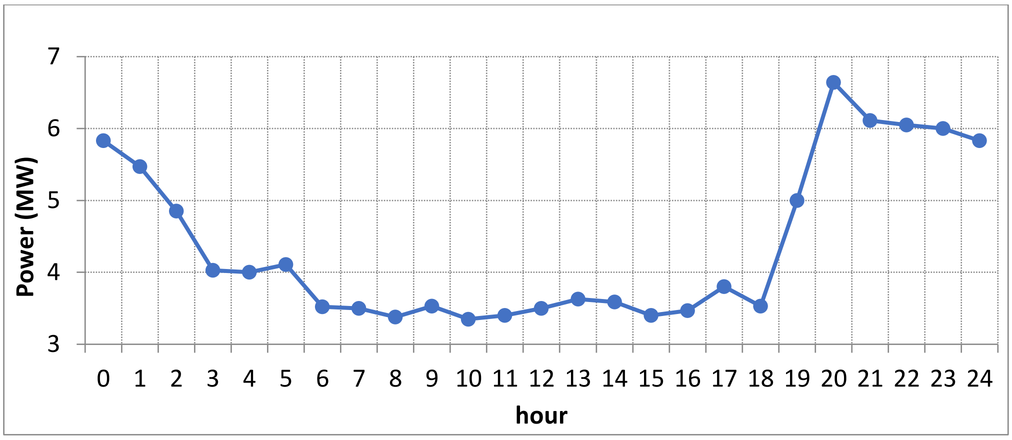
According to the records published by the Central Bank of Egypt for the 2020 year, in this research the average discount rate used is equal to 9.25%. Furthermore, the average inflation rate used is equal to 5%.

3.4. Electricity Supply and Demand Data

Electricity supply in Siwa Oasis is mainly depends on Diesel Generators, 4 MAN Diesel Generators of 21 MW which are going to be wasted in four years, 2 CAT Diesel Generators of 5.2 MW and 1 MAN Diesel Generator 4 MW for emergency (El Zahraa Magdy, Ibrahim & Sabry, 2020), besides a 10 MW solar thin film PV power plant. Unfortunately, many panels in the solar thin film PV power plant are destroyed or do not work properly, hence it is working with about 60% to 70% of its efficiency, which require a necessary maintenance.

The explained negative existing DGs and PV factors impose a shortage in supplying the load which is already light load, where varies between 3 and 7 MW only as shown in Fig. 2 (El Zahraa Magdy, Ibrahim & Sabry, 2020). Additionally, according to the interview conducted with Saleh and Adel the technicians in Siwa Oasis power plant, the load sometimes could reach to more than 9 MW as it is slightly rise besides the variation in load requirements across the year due to difference in required load per month or season side by side the increased visits to Siwa Oasis by tourists and the new commercial and industrial electrical requirement. Therefore, the obtained daily load sample (Fig. 2) will be considered with 20% random variation due to the mentioned factors that are increasing the required loads which will make a monthly variation as shown in figure 4.7. As a result of this assumption, the average load estimated by HOMER Pro to be 103,680 kWh/day for the peak of about 11,337.19 kW.

Figure 2. Sample of Daily Load Profile in Siwa Oasis.



4. Optimal System Configurations

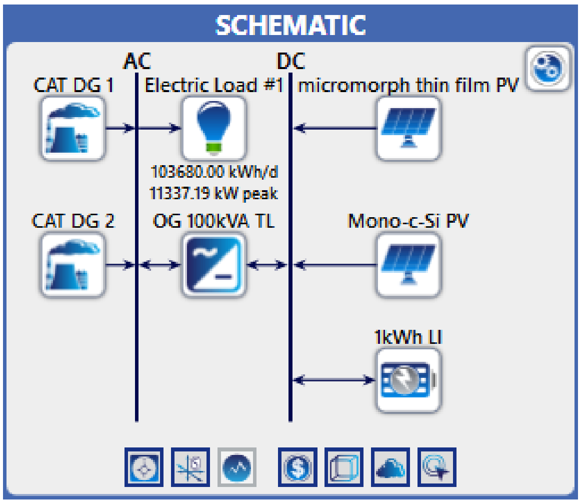
In this section, the optimal system configuration will be analyzed by HOMER Pro according to many constraints besides the illustrated mereological data, electrical data, and cost variables as the following:

- The existing 4 MAN diesel generators of 21 MW will be neglected in the analysis as they are going to be wasted in four years as discussed previously.
- The Monocrystalline PV panel type that will be used in the optimization is considered due to its fine price for its efficiency and availability in the Egyptian market. In general, the efficiency of crystalline silicon is varying between 13 – 21 %. In this research, the product of JINKO Solar JKM465M-7RL3-V will be used. The power of each panel is 465 Wp, efficiency 20.71%, and the derating factor is 85%. The price for each kW is 605$ including the inverters cost.
- The existing 10 MW solar thin film PV system will be included in the optimization with 60% of its efficiency due to its condition that is explained previously.
- The batteries of lithium-ion prices are lower than other batteries, which is desired for a low LCOE energy source. Hence, lithium-ion batteries will be used in this research with 200$/kWh due to its cost-effective price that is continuously declining (IRENA, 2015).
- The Period of Analysis used is 25 years, which is the expected PV panels lifetime.

4.1. HRES Including Existing Reliable Diesel Generators

The total designed electrical load is 103,680 kWh/day for the peak of about 11,337.19 kW and multiple sources were used such as new optimized PV and existing PV panels, lithium-ion battery storage, and the reliable existing diesel generators to fulfill the electrical consumption. The schematic diagram is shown in Fig 3.

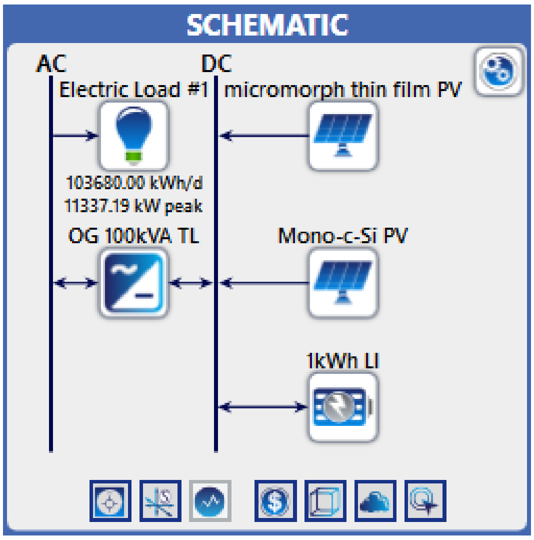
Figure 3. Schematic Diagram of HOMER Pro for the HRES Including Reliable Diesel Generators.



4.2.HRES Excluding Existing Reliable Diesel Generators

In this scenario, the electrical load of 103,680 kWh/day for the peak of about 11,337.19 kW will be designed, and multiple sources are used such as new optimized PV and existing PV panels, and battery storage excluding the existing reliable diesel generators to fulfill the electrical consumption. The schematic diagram is shown in Fig 4.

Figure 4. Schematic Diagram of HOMER Pro for the HRES Excluding Reliable Diesel Generators.



5. Results

5.1. Optimum Solution for HRES Including Existing Reliable Diesel Generators

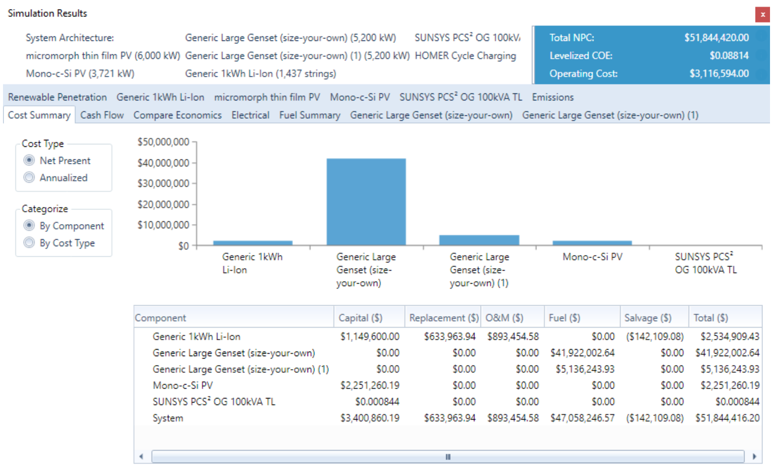
The value of LCOE in this hybrid energy system is 0.0881 $/kWh with the considered components and 3.721 MW of Monocrystalline PV panels optimized as shown in Fig. 5 and Fig. 6.

Figure 5. Optimization Results for the HRES Including Existing Reliable Diesel Generators.

Architecture							Cost			
micromorph thin film PV (kW)	Mono-c-Si PV (kW)	CAT DG 1 (kW)	CAT DG 2 (kW)	1kWh LI	OG 100kVA TL (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
6,000	3,721	5,200	5,200	5,748	8,440	CC	$51.8M	$0.0881	$3.12M	$3.40M
6,000		5,200	5,200	5,736	9,566	CC	$52.8M	$0.0897	$3.32M	$1.15M
6,000		5,200	5,200		5,669	CC	$55.9M	$0.0951	$3.60M	$0.000567
6,000	1,220	5,200	5,200		8,592	CC	$56.1M	$0.0954	$3.56M	$738,075
6,000	3,715	5,200		19,236	12,549	CC	$57.3M	$0.0974	$3.29M	$6.09M
6,000	3,715		5,200	19,236	12,549	CC	$57.3M	$0.0974	$3.29M	$6.09M
6,000		5,200		19,020	16,933	CC	$58.3M	$0.0992	$3.51M	$3.80M
6,000			5,200	19,020	16,933	CC	$58.3M	$0.0992	$3.51M	$3.80M
6,000	91,740			125,492	14,103	CC	$111M	$0.189	$1.95M	$80.6M

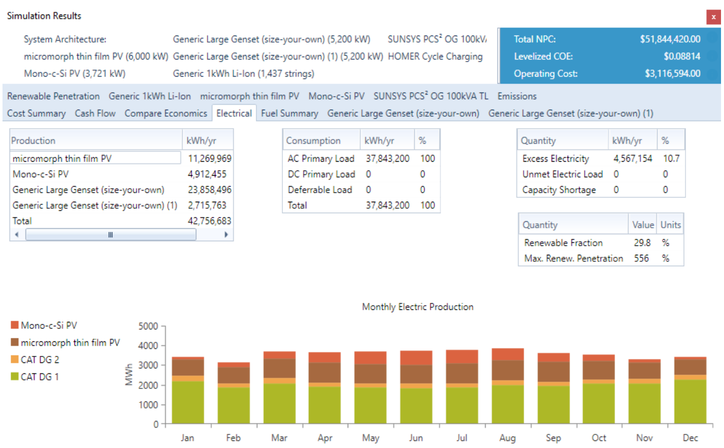
Furthermore, the total NPC for this system is $51,844,420 and the capital cost is $3,400,860.19, knowing that the discussed existing reliable diesel generators are included in the optimization with the fuel price regardless its capital cost. In addition, existing solar thin film PV panels are included in the optimization regardless its capital cost also.

Figure 6. Cost Summary for the HRES Including Existing Reliable Diesel Generators.



The electrical production conclusion of the HRES including existing reliable diesel generators that is resulted shows that for this system, the unmet electric load is zero. However, the production is 42,756,683 kWh/year as shown in Fig. 7.

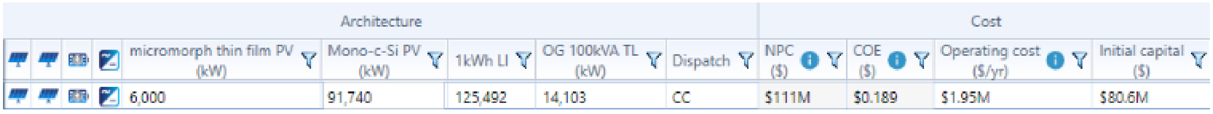
Figure 7. Electrical Production Details of the HRES Including Existing Reliable Diesel Generators.



5.2. Optimum Solution for HRES Excluding Existing Reliable Diesel Generators

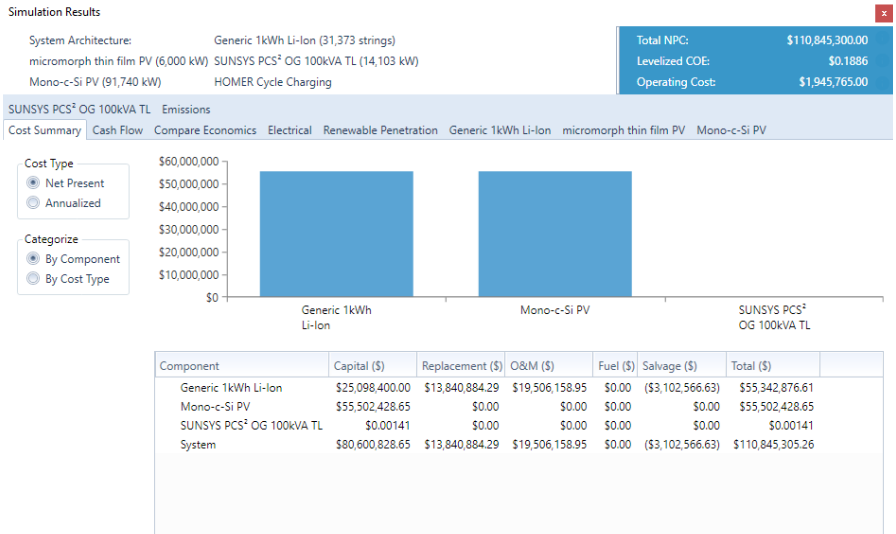
With the considered components and 91.74 MW of Monocrystalline PV panels optimized, the value of the LCOE in this scenario of hybrid energy system is $0.1886/kWh, which is higher than the HRES including the existing reliable diesel generators, while the total NPC for this system is $110,845,300 and the capital cost is $80,600,828.65 as shown in Fig. 8 and Fig. 9.

Figure 8. Optimization Results for the HRES Excluding the Existing Reliable Diesel Generators.



Architecture					Cost			
micromorph thin film PV (kW)	Mono-c-Si PV (kW)	1kWh LI	OG 100kVA TL (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
6,000	91,740	125,492	14,103	CC	$111M	$0.189	$1.95M	$80.6M

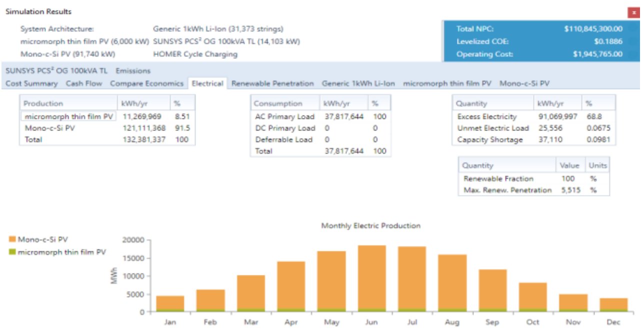
Figure 9. Cost Summary for the HRES Excluding the Existing Reliable Diesel Generators.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Generic 1kWh Li-Ion	$25,098,400.00	$13,840,884.29	$19,506,158.95	$0.00	($3,102,566.63)	$55,342,876.61
Mono-c-Si PV	$55,502,428.65	$0.00	$0.00	$0.00	$0.00	$55,502,428.65
SUNSYS PCS² OG 100kVA TL	$0.00141	$0.00	$0.00	$0.00	$0.00	$0.00141
System	$80,600,828.65	$13,840,884.29	$19,506,158.95	$0.00	($3,102,566.63)	$110,845,305.26

The electrical production conclusion of the HRES excluding reliable diesel generators resulted shows that for this system, the unmet electric load is 0.0675% which contributing to the capacity shortage with about 37,110 kWh/year as shown in Fig. 10.

Figure 10. Electrical Production Summary for the HRES Excluding Diesel Generators.



Production	kWh/yr	%
micromorph thin film PV	11,269,969	8.51
Mono-c-Si PV	121,111,368	91.5
Total	132,381,337	100

Consumption	kWh/yr	%
AC Primary Load	37,817,644	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	37,817,644	100

Quantity	kWh/yr	%
Excess Electricity	91,069,997	68.8
Unmet Electric Load	25,556	0.0675
Capacity Shortage	37,110	0.0981

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	5,515	%

5.3. Environmental Aspect

The associated emissions of the proposed scenarios are relating to the diesel generators working times. The associated emissions of the proposed systems and the eliminated diesel generators is shown in Table 1.

Table 1. Comparison Between Different Scenarios Emissions.

Name	Emissions (kg/year)		
	Eliminated Diesel Generators	**HRES Including Existing Reliable Diesel Generators**	**HRES Excluding Existing Reliable Diesel Generators**
Carbon Dioxide	26,225,737	18,419,286	0
Carbon Monoxide	135,678	95,292	0
Unburned Hydrocarbons	7,201	5,057	0
Particulate Matter	1,160	815	0
Sulfur Dioxide	64,108	45,025	0
Nitrogen Oxides	26,003	18,263	0

Eventually, it is obvious form the obtained results that the HRES including the existing reliable diesel generators is highly recommended to be adopted instead of the HRES excluding reliable diesel generators as the first scenario LCOE is 0.0881 $/kWh, while the second scenario LCOE is 0.1886 $/kWh. Moreover, the difference in total NPC between these two configurations is slightly exceeds $59 million. On the other hand, despite the 18,419,286 kg of CO_2 emitted per year by the nominated scenario which has the lowest LCOE, 26,225,737 kg of CO_2 per year have been eliminated by neglecting the unreliable diesel generators.

6. Conclusion

HRES is considered to meet the unmet electrical loads and eliminate capacity shortages. Diesel generators are not satisfying the required electrical demand, moreover, they are committed for a great amount of emissions. The proposed HRES including the existing reliable diesel generators analysis concludes that the proposed design of the energy system increases the capital cost of the HRES excluding the existing reliable diesel generators by approximate $77.2 million and $59 million in the NPC. The unmet load indicates a slight increase from zero to 0.0675% for the HRES excluding existing reliable diesel generators scenario.

Whereas the LCOE increased from 0.0881 $/kWh to 0.1886 $/kWh. Based on this study, in spite of the discussed emission results that were showed an excessive contribution of the existing diesel generators in its operation phase on the environment for many environmental impact categories, it is extremely recommended to implement the proposed HRES including diesel generators to meet the increased electrical requirements of Siwa Oasis rather than the HRES excluding diesel generators, due to the convenience and accessible renewable energy resources, as it locates in the sunbelt region with a low cost per kWh and the intensive difference in capital cost and NPC between these two scenarios.

In future studies, better energy management system and utilizing more energy efficiency applications can fill the gap between supply and demand, which will extremely raise the overall efficiency of the system. Additionally, adopting sustainable development in such regions will meet the electrical demand and a great reduction in relying on fossil fuel-based energy sources, while the preservation of environment is obtained.

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