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Simulation-Based Analysis of Solar PV-Diesel Hybrid System Upgrades Using Helioscope & HOMER Pro

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***Abstract* -** This paper presents a simulation-based case study evaluating proposed upgrades to an existing solar photovoltaic (PV)-diesel hybrid energy system at a remote commercial hatchery in Al Lith, Saudi Arabia. Using HelioScope and HOMER Pro software, three scenarios were analysed: the current PV-diesel system, integration with battery energy storage systems (BESS), and a fully renewable, zero-emission configuration. The techno-economic and environmental assessments indicate that incorporating BESS and expanding rooftop PV capacity (Scenario 1, Option B) offers the optimal path forward, reducing fuel consumption by 23% and carbon emissions by 24% compared to the baseline. This configuration significantly shortens the system's payback period and reduces the levelized cost of energy (LCOE) to $0.0819/kWh. Although the fully renewable system (Scenario 2) results in zero fuel use and emissions, it is deemed financially and spatially unfeasible due to its high capital cost, land requirements, and large-scale battery storage demands. The results underscore the economic viability of optimized hybrid systems with moderate renewable integration in off-grid or weak-grid contexts. The study also illustrates the critical role of diesel price fluctuations, which significantly affect the economic metrics of hybrid and renewable energy investments. Recommendations are provided for commercial facility operators, researchers, and policymakers, including the utilization of targeted financing schemes such as Saudi Arabia's Mutjadeda programme. These findings contribute to the broader discourse on sustainable energy transitions in remote commercial settings, offering actionable insights for reducing reliance on diesel generation through technically and economically balanced renewable energy solutions.

***Keywords*:** Solar PV, HOMER Pro, Helioscope, Diesel Hybrid Systems, Renewable Energy, Battery Energy Storage Systems

1. Introduction

Remote regions heavily dependent on diesel generators for electricity face significant financial burdens due to fuel costs, transportation logistics, and operational expenses [1], alongside the serious environmental concerns arising from fossil fuel emissions [2]. Transitioning to renewable energy solutions presents an opportunity to mitigate those challenges. This research investigates the feasibility of enhancing an existing solar-diesel hybrid energy system at a commercial hatchery facility located in Al Lith, Saudi Arabia – a remote location with abundant solar resources yet challenging infrastructure conditions. Utilizing advanced simulation software tools such as Helioscope and HOMER Pro, this study explores various renewable energy upgrade configurations aimed at improving sustainability, reducing operational costs, and minimizing environmental impacts.

2. Site Conditions

2.1. Site Characteristics

The Al Lith site is characterized by rugged terrain, abundant solar irradiance, and extreme seasonal temperatures ranging from 20°C to 45°C [3]. The region receives very little precipitation throughout the year, with an average of only 50 mm of rainfall annually [4]. The landscape is challenging, dominated by mountainous terrain and sandy soils with low organic content and poor water retention, significantly hindering the potential for infrastructure development. These factors contribute to prohibitive costs that render the construction of transmission infrastructure economically unfeasible and limit potential connectivity to local and regional electrical grids.

2.2. Solar Irradiance

Irradiance data essential for optimizing the proposed solar energy system in Al Lith include global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) [5]. GHI, the total solar radiation received on a horizontal surface encompassing direct and diffuse components, averages 5.6 kWh/m²/day in Al Lith. DNI, representing solar radiation perpendicular to the Sun's rays and crucial for concentrating solar power applications, averages 5.8 kWh/m²/day. DHI, indicative of solar radiation scattered by the atmosphere reaching a horizontal surface, averages 1.9 kWh/m²/day [6]. Such irradiance levels position Al Lith among the regions with substantial solar resource availability, thereby strongly indicating the site's high viability and favourable potential for solar PV energy generation.

2.3. Soiling

The accumulation of dust, dirt, and other particulate matter on surfaces such as solar photovoltaic (PV) panels, defined as soiling, significantly impacts their operational efficiency and increases maintenance requirements [7]. The rate and severity of soiling depend on several factors, including geographic location, weather conditions, and the surrounding environment. In various regions of Saudi Arabia, PV system performance degradation due to soiling has been observed to range from approximately 2% to over 50%. Notably, a single sandstorm event has been documented to cause a substantial 20% decrease in PV module output. In Dhahran, PV modules left uncleaned for six months exhibited a performance drop exceeding 50% [8]. This challenge can be mitigated by the implementation of an appropriate maintenance schedule in the operational phase of PV upgrades.

2.4. Existing Electrical System

Prior to the currently operational solar PV upgrade, the hatchery facility relied entirely on diesel generators as it lacked any grid connection capabilities. These diesel generators thus played a critical role in continuously meeting the facility's substantial energy demands. Comprehensive monitoring conducted over a two-year period provided detailed insights into the facility's energy consumption patterns. For instance, energy consumption data collected for a week in March 2019 demonstrated a daily usage averaging around 20,000 kWh. Further annual data collection revealed notable variations in daily and seasonal energy usage, forming essential inputs for the simulation analyses summarized within this paper.

Currently, the hatchery employs four primary 60 Hz Caterpillar diesel generators, each rated at 1 MW (1.25 MVA at 0.8 power factor), plus an additional 1 MW emergency backup unit, totalling 5 MW (6.25 MVA) capacity. Operational practices involve rotating two generators simultaneously while maintaining the remaining units in standby to optimize fuel efficiency and operational costs. Despite the well-maintained condition of these 15-year-old units, rising diesel fuel prices are progressively increasing operational expenditures.

To mitigate rising diesel costs and reduce environmental impacts, the hatchery invested $1,000,000 in a 725 kWp solar PV system in 2020, which was commissioned in 2021. The PV array consists of 1,908 Jinko Solar 380 Wp modules with ratings of 9.75 A Isc, 48.9 Voc, and a peak efficiency of 19.6%. These panels were coupled with 12 SMA STP60 inverters with a maximum input voltage of 1000 V, rated power of 60 kW, and a peak efficiency of 98.8%. The PV system also includes combiner boxes, weather stations, and cables, which are not detailed in this paper. Continuous performance tracking is provided by a VCOM monitoring system, enabling ongoing optimization of the energy output. This integration of solar energy has significantly reduced diesel fuel consumption and operational costs, thereby enhancing the sustainability and economic efficiency of the facility.

3. Methodology

A comprehensive simulation methodology was implemented by combining HelioScope [9] and HOMER Pro [10] software to evaluate the existing solar-diesel hybrid system at the hatchery and analyse potential upgrade scenarios. Initially, HelioScope was utilized to accurately simulate the existing solar-diesel hybrid system layout, annual yield, and performance metrics. The results from HelioScope were validated against actual performance data collected from the facility to ensure accuracy and reliability.

Subsequently, the validated HelioScope simulation results were integrated into HOMER Pro with diesel generator operational data and potential additional solar PV and/or battery energy storage system (BESS) configurations. HOMER Pro provided detailed economic and environmental analyses of various upgrade scenarios, considering key constraints such as available rooftop space and the operational limitations of diesel generators, which must not operate below 30% of their rated capacity according to manufacturer recommendations.

To enhance renewable energy integration and minimize reliance on diesel generators, lithium-ion batteries were selected as the preferred storage solution, primarily due to their favourable cycle life and depth-of-discharge (DoD) characteristics [11]. Specifically, a generic 6 V 1 kWh / 167 Ah lithium-ion battery with an efficiency of 90% was selected from the HOMER Pro library.

The simulations considered three distinct system upgrade configurations, summarized in Fig.1: a hybrid diesel-PV system with additional BESS, the same system with additional PV and BESS, and a fully renewable PV-BESS system. These configurations are incremental upgrades to the current system, targeting increased renewable energy penetration and reduced diesel dependence.

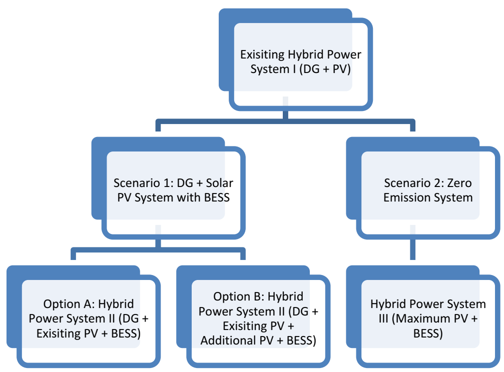

Fig. 1: Hierarchy of the proposed system upgrades

Economic metrics (including capital costs, operational expenses, and levelized cost of energy (LCOE)) and environmental impacts were analysed for each configuration, providing comprehensive insights into the potential advantages and feasibility of each proposed system upgrade.

4. Simulation Results and Analysis

4.1. Existing As-Built Solar PV Diesel Hybrid

To establish a baseline for comparison with each of the proposed solar PV upgrades, simulations of the existing solar-diesel hybrid system were conducted. Accurate replication of the existing 725 kWp solar PV installation was achieved using detailed drawings and site specifications.

The installed solar PV system was replicated in HelioScope utilizing precise module placements, inverter locations, and component selections matching the actual installation. The HelioScope simulation provided detailed performance metrics, predicting an annual production of approximately 1.233 GWh with a performance ratio of 77.6%.

To verify accuracy, HelioScope's simulated results were validated against actual monthly energy production data collected by the engineering, procurement, and construction contractor from July to September 2022, revealing close alignment within a ±10% range. Instances of performance deviation were primarily due to temporary issues such as soiling or minor equipment malfunctions.

To evaluate the integrated solar-diesel hybrid system comprehensively, HOMER Pro simulations combined HelioScope’s solar output data, diesel generator parameters, and the hatchery’s electrical load profile. Using accurate geographic and irradiance data, the existing system was modelled in HOMER Pro (Fig. 2). The simulation indicated monthly energy contributions with the primary diesel generator supplying 76.6% of demand, the secondary generator contributing 6.2%, and solar PV fulfilling 17.2% of total energy requirements.

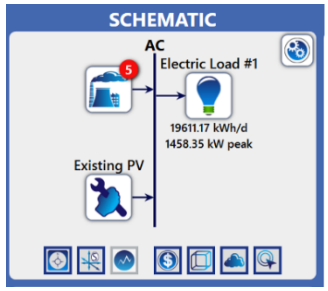

Fig. 2: Existing system schematic on HOMER Pro

The simulation revealed annual excess electricity production of 19,201 kWh (0.268% of total output). Economic analysis indicated an initial capital cost of $1,600,000, net present cost (NPC) of $28,408,670, LCOE of 0.1588 $/kWh, and annual operating costs of $1,072,346, yielding a payback period of approximately 6.4 years.

Fuel consumption analysis assumed a diesel price of $0.44/L, incorporating market and logistical factors. The annual fuel consumption was approximately 1,593,981 litres, averaging 4,367 litres daily, with yearly costs totalling $701,352. The environmental benefits of integrating solar PV were substantial, significantly reducing emissions compared to diesel-only operation (Table 4 in Section 5, below, summarizes the emissions data for the existing system and the two options presented in Scenario 1).

The integration of solar PV substantially lowered LCOE, reduced operational and fuel expenses, and significantly decreased environmental emissions, justifying the investment with an economically viable payback period potentially shortened by rising diesel prices.

4.2. Scenario 1 – Option A (Small Battery Storage Addition)

This option proposed integrating a BESS with the existing 725 kWp solar PV system and two operating diesel generators. The scenario was modelled as per Fig. 3, which optimized the sizing of the battery storage to 471 kWh, considering a Li-ion battery cost of $160 per kWh and an operating and maintenance (O&M) cost of 2%.

Simulation results (Fig. 4, Table 1) indicated that the primary diesel generator provided 82.4% of the facility's energy, while the secondary generator's usage dropped to only 0.438% due to the BESS integration. The solar PV contribution remained consistent at 17.2%, matching the existing configuration. Although the BESS accounted for a negligible amount of total energy consumption, its inclusion enabled a slight reduction in operational time for the second generator, improving overall operational efficiency marginally and slightly reducing fuel consumption.

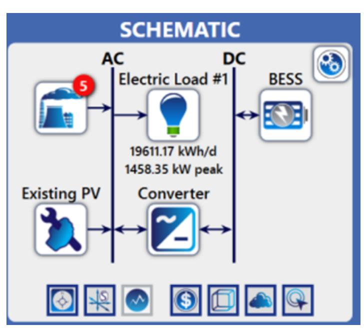

Fig. 3: Scenario 1 Option A schematic on HOMER Pro

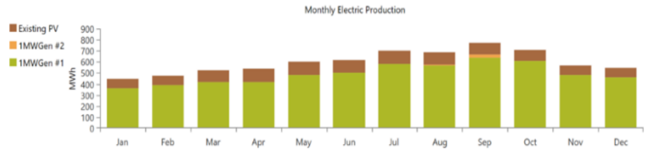

Fig. 4: Monthly electric production of the Option A system using HOMER Pro

Table 1: Summary of energy production

Asset	**Existing System**		**Hybrid System II**	
	kWh/yr	***%***	***kWh/yr***	***%***
Generator 1	5,495,093	76.6	5,915,690	82.4
Generator 2	449,100	6.26	31,471	0.438
Solar PV	1,233,085	17.2	1,233,085	17.2
Total	7,177,277	100	7,180,245	100

The upgraded system resulted in an increased initial capital cost of $1,685,825, an NPC of $17,741,490, an operational cost of $642,226 per year, and a modestly improved LCOE of $0.0991/kWh. The payback period increased to 9.4 years compared to the previous configuration, showing that the excess increase in clean energy from the new BESS installation has a significant impact on the financial metrics and a minimal impact on the overall generation of the system.

Annual diesel fuel consumption decreased slightly to 1,575,189 litres, corresponding to an average daily usage of approximately 4,316 litres and annual fuel costs of $315,037. Consequently, emissions showed a modest decrease of around 1.2%. Notably, carbon dioxide emissions were reduced to 4,130,501 kg per year, with carbon monoxide reduced to 21,369 kg per year, i.e., a 1.2% reduction (Table 4 in Section 5 summarizes the emissions data for both options in Scenario A).

In summary, the addition of a BESS provided limited but measurable environmental improvements to the solar-diesel hybrid system. While benefits included marginal reductions in operational and fuel costs and a slight decrease in emissions, these modest gains must be weighed against the higher initial capital investment required for battery integration.

4.3. Scenario 1 – Option B (Expanded Rooftop PV and Larger BESS)

This scenario considered the integration of a larger BESS and an additional 900 kWp rooftop solar PV system to maximize utilization of available rooftop space. Due to space constraints, this expansion was limited to 900 kWp using the latest Jinko Solar modules. The upgraded scenario was simulated, which sized an optimized BESS with an increase in capacity to 2,627 kWh as shown in Fig. 5. The optimized scenario resulted in increased renewable energy penetration, with 38.1% of total energy sourced from solar PV. Specifically, 16.4% came from the original PV array and an additional 21.7% from the newly installed rooftop system, while the primary diesel generator provided 61.9% (Table 2). The secondary diesel generator was completely shut down, significantly reducing diesel dependence.

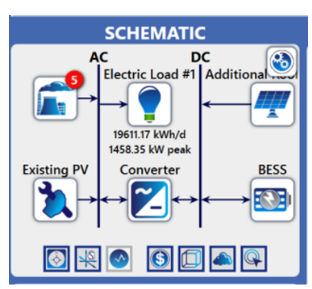

Fig 5: Scenario 1 – Option B schematic on HOMER Pro

Table 2: Summary of energy production

Asset	Existing System		Hybrid Power System II	
	kWh/yr	***%***	***kWh/yr***	***%***
Generator 1	5,495,093	76.6	4,661,925	61.9
Generator 2	449,100	6.26	0	0
Existing Solar PV	1,233,085	17.2	1,233,085	16.4
Additional Solar PV	N/A	N/A	1,637,774	21.7
Total	7,177,277	100	7,532,784	100

Annual diesel fuel consumption decreased significantly to 1,211,108 litres, approximately 3,318 litres per day, reducing annual fuel expenses to $242,221 – a 23% reduction compared to previous scenarios. This reduction contributed to considerable emission reductions, notably decreasing annual carbon dioxide emissions to 3,175,797 kg and carbon monoxide emissions to 16,430 kg, i.e., a reduction of 24 % (all emissions data is summarized in Table 4 in Section 5, below).

The estimated cost of the additional PV installation was $360,000 at a market rate of $0.4/Wp. The initial capital cost increased to $2,121,305, while the NPC improved substantially to $14,650,930, and the operational cost reduced to $501,185 annually. The LCOE further decreased to $0.0819/kWh, resulting in a shorter payback period of approximately 6.1 years.

In summary, the addition of further solar panels and a significantly larger BESS significantly enhanced renewable energy integration and overall economic and environmental performance compared to previous configurations, despite higher initial investment costs.

4.4. Scenario 2 – Zero-Emission System (Fully Renewable Option)

The final scenario aimed for a fully renewable, zero-emission configuration by removing all diesel generators and significantly expanding solar PV capacity. This scenario integrated the previously discussed 725 kWp existing system, the additional 900 kWp rooftop system (Scenario 1 – Option B), and a new ground-mounted solar PV installation to meet the facility's entire energy demand. Due to space constraints on-site, an extensive ground-mounted PV system of 6.4 MWp was modelled, requiring approximately 39,623 m² of land – the equivalent of almost the total area occupied by the hatchery. The proposed schematic for Scenario 2 is depicted in Fig. 6.

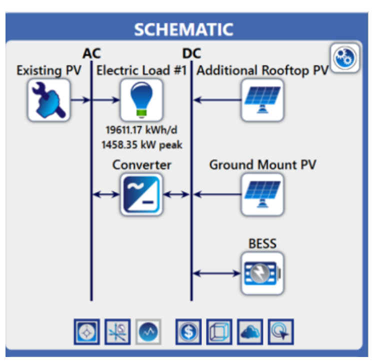

Fig. 6: Scenario 2 schematic on HOMER Pro

Simulation results from HOMER Pro indicate that the ground-mounted PV system provides 80.3% of the facility's annual energy, while the rooftop expansions and the existing solar PV system contribute 11.3% and 8.48% (Table 3). To complement the significant increase in solar capacity, a large BESS of 39.6 MWh was implemented, ensuring a system autonomy of 33.9 hours.

Table 3: Summary of energy production

Asset	Existing System		Hybrid Power System III	
	kWh/yr	***%***	***kWh/yr***	***%***
Generator 1	5,495,093	76.6	N/A	N/A
Generator 2	449,100	6.26	N/A	N/A
Existing Solar PV	1,233,085	17.2	1,233,085	8.48
Additional Solar PV	N/A	N/A	1,637,774	11.3
Ground Solar PV	N/A	N/A	11,671,871	80.3
Total	7,177,277	100	14,542,730	100

Although the system entirely eliminates diesel consumption, thus significantly reducing operational expenses, the initial capital investment is substantially higher than the previous options, totalling $10,633,842. The NPC of the system reaches $21,002,020 with an LCOE of $0.1174/kWh and annual operating costs of $414,727.

Despite achieving zero emissions and eliminating fuel expenses, the high capital costs and significant land requirements associated with this option may present practical and financial challenges for stakeholders considering transitioning to a fully renewable system.

5. Discussion and Recommendations

This study has evaluated three main upgrade scenarios for enhancing the sustainability and economic efficiency of the existing solar-diesel hybrid system at the hatchery facility. Scenario 1 (Option A) involves the integration of a 471 kWh BESS, which presents a relatively modest initial capital cost. It offers a reduction in the LCOE, decreased O&M costs, slightly lowered fuel consumption, and a marginal reduction in emissions.

Scenario 1 (Option B) significantly increases renewable energy penetration to 38.1% by incorporating an additional 900 kWp rooftop solar PV system along with a larger 2,627 kWh BESS. This enhanced configuration enables the near-complete shutdown of one diesel generator, substantially reduces the load on the remaining generator, and leads to a reduced payback period. Option B provides considerable benefits, including further reduced LCOE, substantial O&M cost savings, significant emission reductions, and notably lower fuel consumption. The simulated emissions data for Options A and B of Scenario 1 are shown in Table 4, below, compared to the figures generated by the existing system.

Scenario 2 involves the addition of 6.4 MWp ground mount solar in addition to the existing rooftop solar and the proposed additional rooftop solar in Scenario 1 (Option B), along with a large 39.6 MWh BESS. Despite providing full autonomy from fossil fuels, with the environmental and financial benefits that creates, the NPC is prohibitive.

Table 4: Summary of simulated emissions data for Scenario 1 – Options A and B

Quantity of	Value (kg/year)	Scenario 1 – Option A	% Change	Scenario 1 – Option B	% Change
Carbon Dioxide	4,179,778	4,130,501	-1.2	3,175,797	-24.02
Carbon Monoxide	21,624	21,369	-1.16	16,430	-24.02
Unburned Hydrocarbons	1,148	1,134	-1.22	872	-24.02

Quantity of	Value (kg/year)	Scenario 1 – Option A	% Change	Scenario 1 – Option B	% Change
Particulate Matter	185	183	-1.08	140	-24.02
Sulfur Dioxide	10,217	10,097	-1.15	7,763	-24.02
Nitrogen Oxides	4,144	4.096	-1.16	3,149	-24.02

External funding may be secured via bodies such as the Saudi Industrial Development Fund (SIDF) and its renewable refinancing program, Mutjadeda, which offers financing for up to 75% of renewable project costs with an extended repayment period of up to 15 years, which would make Scenario 2 feasible.

In the absence of such funding, Scenario 1 (Option B) is the recommendation for the renewable upgrade at the facility.

6. Conclusion

Simulations highlighted that enhancing an existing solar-diesel hybrid system through expanded rooftop solar PV and an appropriately sized battery storage system (Option B) delivers significant environmental and economic advantages. This research has significant practical implications because the approach recommended in it can serve as a model for similar remote and off-grid applications.

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