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Techno-economic analysis of hybrid photovoltaic and stirling engine generator for offshore oil and gas platform

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ABSTRACT

The increasing demand for sustainable offshore oil and gas operations has driven the exploration of efficient and environmentally friendly hybrid energy systems. Conventional fossil fuel-based systems' consumption significantly contributes to greenhouse gas emissions and creates a need for innovative solutions that address environmental challenges while maintaining operational effectiveness. This study aims to analyse and evaluate a hybrid energy system that combines Stirling Engine Generator (SEG) technology and Photovoltaic (PV) panels, with the primary goal of enhancing energy efficiency, reducing carbon emissions, and improving the sustainability of offshore oil and gas operations. A comprehensive approach, integrating manual calculations and PVsyst software simulations, was used to analyse the performance of the Stirling and PV hybrid system. The research findings indicate that the hybrid system significantly improves energy efficiency and carbon emissions reduction compared to a fossil fuel-based system, with SEG utilizing heat from natural gas combustion and PV panels capturing solar energy, creating a synergistic effect with better overall performance and a lower environmental impact. Economically, the hybrid system minimizes fuel dependency and maintenance costs, benefiting from PV panels' lower operational expenses compared to a fuel-based system. This combination not only aids emission reduction efforts but also presents a cost-effective solution over time, with the system's ability to harness renewable energy and support compliance with emission reduction regulations. In conclusion, integrating SEG and PV technologies in a hybrid system offers a practical pathway to achieving emission reduction targets and maintaining operational efficiency, marking a step toward environmentally and economically sustainable practices in offshore oil and gas operations.

INTRODUCTION

Currently, offshore oil and gas operations are still highly dependent on fossil-based power generation systems (diesel oil) (Khurshid, Mohammed, Al-Yacouby, et al., 2024), which causes increased carbon emissions (Emission & Platforms, 2019; Romasheva & Cherepovitsyna, 2023) and high power plant operating costs. This research was conducted to examine the main issues and mitigate fossil fuel dependence and greenhouse gas emissions on offshore platforms (Khurshid et al., 2024) by introducing a hybrid power generation technology system that combines Stirling Engine Generator (SEG) technology and Photovoltaic (PV) (Amiri et al., 2021; Arslan & Kocakulak, 2023; Perozziello et al., 2021; Taki et al., 2019). This is different from traditional hybrid power generation systems that mostly combine PV with diesel generators. This study presents SEG as a versatile and low-emission alternative power plant (Cherepovitsyn & Rutenko, 2022), especially beneficial for offshore area applications. This study techno-economic analysis was addressed the critical challenge of reducing fuel dependency and greenhouse gas emissions in offshore oil and gas platforms by proposing a hybrid power system integrating Striling Engine Generator (SEG) technology, and Photovoltaic (PV) panels, with the objectives of this study to evaluate the technical feasibility of a hybrid PV-SEG-Battery system, and to reduce CO_2 emissions reduction (Serra & Fancello, 2020).

The research findings indicate that the hybrid system significantly improves energy efficiency and reduces carbon emissions compared to fossil fuel-based systems, with SEG utilizing heat from natural gas external combustion and PV panels capturing solar energy, creating a synergistic effect with better overall performance and a lower environmental impact. This fossil fuel dependency problem must be resolved immediately so that the diesel used in platform operations can be utilized by communities that need it more (Antunes et al., 2024; Belucio et al., 2022).

Several previous studies have explored various hybrid power generation systems, such as those using a hybrid PV-Diesel, PV-Battery, PV-Wind turbine, and PV combined with a Thermoelectric Generator (TEG) (Hilmi et al., 2024), to achieve better results (Braga et al., 2022; Igogo et al., 2021; Yimen et al., 2020). However, what researchers have never studied before is a hybrid system that combines SEG and PV, where SEG produces significantly lower gas emissions than Diesel Engine Generator (DEG) and Closed Cycle Vapor Turbogenerator (CCVT), and uses it very economically.

The technological constraint on the proposed solution for this hybrid power plant is that the available SEGs are not ATEX compliant, requiring discussions with safety personnel regarding any additional installations required (Li et al., 2021). This work will significantly contribute to the daily operations of the offshore platform. This includes eliminating the use of diesel for DEG on the platform, as it has been replaced with PV. Natural gas from wells on each platform can be used for SEG, with a much lower consumption compared to CCVT. A backup battery on the platform can be used for up to four days (Lee et al., 2021), preventing power supply shutdowns when SEG and PV encounter problems. Oil and gas production can continue operating while awaiting the arrival of the team to intervene and improve maintenance efficiency (Uhanto et al., 2024; Yuan et al., 2020).

The expected result of this work is energy efficiency, carbon emissions reduction, and improved sustainability of offshore oil and gas operations. Likewise, old offshore platforms still in production should begin switching from conventional electric generation, such as Diesel Engine Generator (DEG) and Closed Cycle Vapour Turbogenerator (CCVT), to Photovoltaic (PV) and Stirling Engine Generator (SEG). Furthermore, the system shows strong resilience under varying fuel price and solar resource scenarios.

While detailed investigations into this hybrid system are few, papers in hybrid technology and (energy) storage journals, e.g., Igogo et al., (2021), Yuan et al., (2020), and Lee et al., (2021), while the latter two serve as theoretical references. Chudy-Laskowska & Pisula (2022), Yimen et al. (2020), Faturachman et al. (2021), and Wang & Simonson (2025) provide theoretical grounding for the techno-economic design of renewable energy. Meanwhile, Brkic D and Stajic Z present explosion protection (Brkic & Stajic, 2021).

This study aims to address the gap in existing research by conducting a techno-economic analysis of SEG and PV hybrid systems specifically for offshore oil and gas operations. This approach is novel in that it evaluates the technical feasibility and economic viability of these hybrid systems in offshore environments. By examining capital and operational costs alongside energy performance metrics, this study contributes to a deeper understanding of the potential for SEG and PV hybrid systems to optimize energy sustainability in offshore oil and gas operations. The results will offer valuable insights for decision-makers considering renewable energy integration in offshore industries, supporting the transition toward more sustainable energy practices.

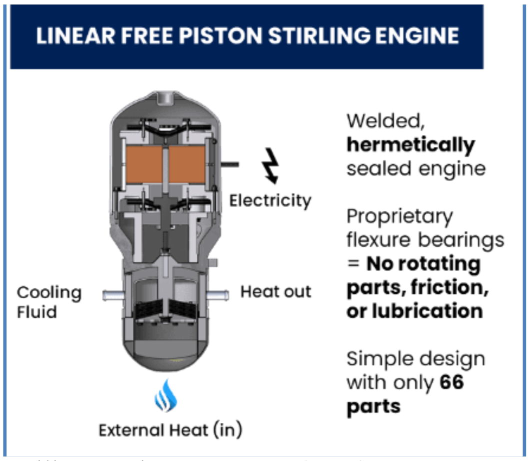
METHODS

In this study, the equipment has been designed with careful consideration of the hazardous conditions present on the offshore platform. The SEG (Stirling Engine Generator) choose did not suitable for hazardous areas, classified as Class I, Div 2, Group D, with a temperature rating of T3. The PV (Photovoltaic) system complies with the ATEX code Ex II 2 G e mb II C T6 GB, and additionally, the battery is put in an Ex e Box (Brkic & Stajic, 2021; Geng et al., 2020).

Concept Design

The proposed hybrid system design integrates a 1,800-watt model 1800 Series, commonly used to supply electrical energy on offshore platform, with a 350 Wp monocrystalline PV, the details of which can be seen in Figure 2 and Table 1.

Photovoltaic (PV)



Striling Engine Generator (SEG)

Figure 2. Hybrid Material

This system is designed so that the SEG can function during bad weather, when the intensity of sunlight is low, while the PV panels contribute during sunny weather. Combining these two technologies aims to increase energy efficiency and reduce dependence on fossil fuels. Figure 3 illustrates the proposed hybrid system design, showing the interaction between SEG and PV panels in creating a more efficient and environmentally friendly energy solution.

Table 1. Material Data Specification

Material Type	Stirling Engine Generator (SEG)	Photovoltaic (PV)
Type	1800	Monocrystalline
Nominal Voltage	24 VDC	24 VDC
Rated Power	1,800 Watts	350 Wp
Dimension	1,764x714x1,453 mm	1,968 x 987 x 40 mm
Natural Gas	1,300 ft3/day (NG)	NO
Weight	392 kg	23 kg

To ensure stable energy availability, the system is equipped with batteries for energy storage. These batteries are a backup when one of the main generators cannot meet energy needs. With this storage system, the energy produced by both SEG and PV panels can be stored and used when needed, increasing the flexibility and resilience of the system (Hannan et al., 2021; Rey et al., 2023; Shamarova et al., 2022). A battery storage system, in general, is shown in Figure 4.

Figure 3. Hybrid System SEG and PV

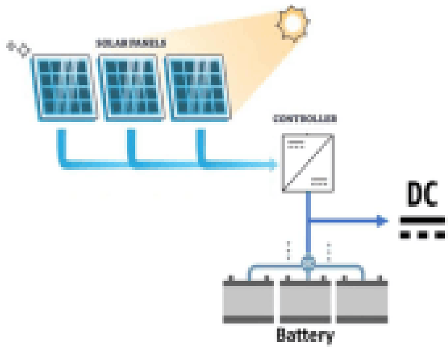


Figure 4. Battery Storage (Rey et al., 2023)

The layout of the photovoltaic (PV) and Stirling Engine Generator (SEG) systems on the upper deck of an offshore platform is shown in Figure 5. The PV panels are placed in areas that receive maximum sunlight exposure to optimize energy production, while the SEG unit is positioned near the gas system on the platform to optimally utilize natural gas combustion. This arrangement is designed to maximize the efficiency of both systems simultaneously in the challenging offshore environment.

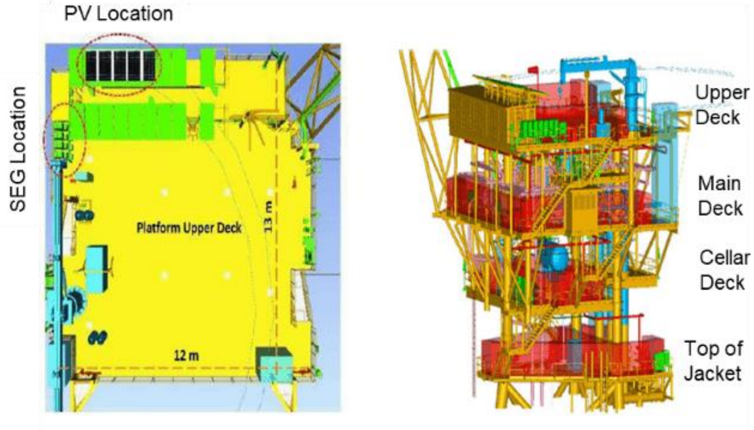


Figure 5. Placement of SEG and PV at the Upper Deck

Calculation Method

The sizing calculation for this hybrid system aims to determine the optimal capacity of the main components, such as the Stirling Engine Generator (SEG), PV panels, and batteries. The system is designed with a configuration of 60% power contribution from SEG and 40% from PVs and batteries. SEG provides the majority of the energy supply to ensure stability, especially when solar radiation is low or absent. Meanwhile, PVs generate 40% of the energy, with sizes adjusted through PVsyst simulation. This contribution from PVs helps reduce fuel consumption by SEG, thus reducing significant CO_2 emissions (Romasheva & Cherepovitsyna, 2023; Serra & Fancello, 2020). The batteries serve to store excess energy from PVs and provide power when PV production decreases, ensuring continuous energy supply and optimal efficiency (Lee et al., 2021). The calculation of the sizing equipment performed is based on the daily energy demand of the various devices in the system, as shown in Table 2.

Table 2. Load Assumption

No	Equipment Name	Load (W)
A	SSS Panel	373.85
B	Radio Communication	15.34
C	Sand Monitoring System	15.96
D	Others	28.9
E	General Alarm System	38.93
F	Nav Aid System	74.54
G	[G = A+B+C+D+E+F]	547.52
H	Floating current to maintain a full charge	43.16
I	Total [I = G + H]	590.68

After the load above is obtained, the capacity of the SEG can be calculated. The sizes of the SEG can be seen in the following Table 3.

Table 3. SEG Sizing

Description	Value	Unit	Remarks
A Power of SEG			
A.1 Rated Power	1,800	Watt	
A.2 Nominal Voltage	24	VDC	
A.3 Rated Power@ 35deg C	1,440	Watt	Note: 1
B Consumer Load			
B.1 Load List * 60%	354.408	Watt	Table. 2
C SEG Required			
C.1 Round-Up	0.246	Units	B.1 / A.3
SEG Installed	1	Units	

Note Rated Power@35deg C Temperature as vendor recommendation.

The sizing calculation of the battery and photovoltaic (PV) panel system is performed using PVsyst software (González-Peña et al., 2021; Razmjoo et al., 2023), as shown in Figure 5. It shows the PV and battery configuration manages

40% of the load, as shown in Table 2 above, and battery autonomy is 4 days.

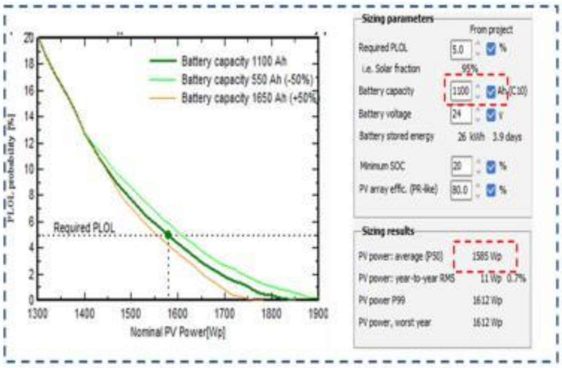


Figure 5. Battery and PV Sizing Calculated by PVsyst

Note: 1585 WP (PV Syst)/350 WP (Data Sheet in Table 1) = 4.5 Units or 5 Units

In addition to the equipment sizing calculations above, hybrid system performance simulations are performed with PVsyst software to evaluate the performance of photovoltaic (PV) systems (Chauhan et al., 2020; Kumar et al., 2020; Razmjoo et al., 2023). The points, which are the factors calculated in the performance evaluation using PVsyst, are shown in Table 4.

Table 4. Parameter Calculation

No	Parameter	Value	Unit	Remarks
A	Orientation			
1	Tilt	21.50	degree	East Borneo
2	Azimuth	0	degree	
B	User needs			
1	Daily Load	236.27	W/app	40% Load
2	Daily use	24	h/day	
C	Detail pre-sizing			
1	PLOL	5	%	
2	BATT	1115	Ah	
3	Battery (V)	24	V	
4	Min SOC	20	%	
5	PV efficiency	80	%	
D	Select PV Module			
1	Manufacturer	SunPower		
2	Module	350	Wp	Monocrystalline
3	Controller	MPPT		
4	Control (W)	1000	W	
E	PV Array Design			
1	PV Series	1	ea	
2	Strings	5	ea	Parallel
F	Storage			
1	Type	Lead-acid		
2	Manufacturer	Sonnenschein		
3	Short battery	Voltage		
4	Voltage/cell	2	V	
5	Capacity	680	Ah	
6	Temperature	Avg ambient		
7	Fixed temp.	35	°C	Ambient temp

The performance of the system is assessed based on several key points, namely the energy generated per unit of installed power, which measures how efficiently the PV system utilizes its installed capacity to generate electricity. In addition, the energy generated based on the performance ratio

(PR) is also evaluated, where PR describes the ratio between the actual energy generated and its ideal energy potential, giving an idea of how effectively the system works under real conditions. The SOC (State of Charge) (Dufo-López et al., 2021; Majeed et al., 2020) condition of the battery throughout the year is also a key metric, indicating the charge and discharge rate of the battery during operation, reflecting the ability of the system to store and provide energy reliably. Evaluation of these three metrics provides a comprehensive understanding of the overall performance of the renewable energy system. The points visualized in the form of graphs can be seen in Tables 5, 6, and 7.

Table 5. Energy generated per unit of installed capacity by PVsyst

Month	kWh/kWp/day			
	Lu	Lc	Ls	Yf
Jan	0.3	0.73	0.54	3.25
Feb	0.47	1.10	0.30	3.25
Mar	0.71	1.36	0.29	3.25
Apr	0.93	1.64	0.36	3.25
May	0.98	1.69	0.32	3.25
Jun	0.95	1.63	0.44	3.25
Jul	1.50	2.29	0.35	3.25
Aug	1.48	2.24	0.36	3.25
Sep	1.17	0.91	0.34	3.25
Oct	0.36	0.96	0.35	3.25
Nov	0.24	0.83	0.30	3.25
Dec	0.14	0.67	0.08	3.25
Year	0.76	1.42	0.34	3.25

Table 5 shows that the annual average useful energy delivered to the load (Yf) remained constant at 3.25 kWh/kWp/day throughout the year. The highest collection loss (Lc) was observed in July at 2.29 kWh/kWp/day, while the lowest occurred in December at 0.67 kWh/kWp/day. Unused energy (Lu) varied significantly, ranging from 0.14 kWh/kWp/day in December to 1.50 kWh/kWp/day in July.

The results indicate that solar energy availability is strongly influenced by seasonal conditions. Higher Lc and Lu values during July and August suggest increased solar irradiance, leading to greater PV production than the load and battery system can fully utilize. Conversely, lower values during November and December indicate reduced solar availability. Despite these variations, the constant Yf value demonstrates that the hybrid SEG-PV system is capable of maintaining a stable energy supply throughout the year (Razmjoo et al., 2023; Nguyen & Lauwaert, 2020).

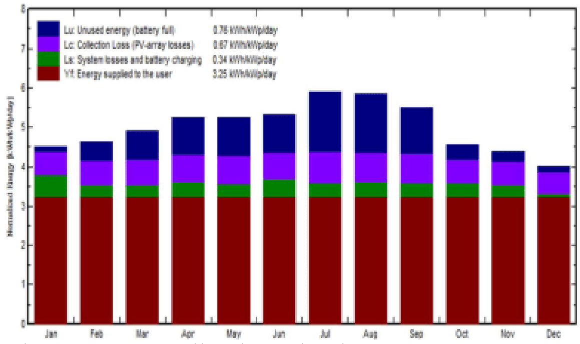


Figure 6. Normalized Production

Figure 6 confirms that the final yield (Yf) remains relatively stable throughout the year despite fluctuations in collection losses and unused energy. This finding indicates that the battery storage system effectively compensates for variations in solar energy generation and contributes to system reliability under offshore operating conditions. Next, Ls (system losses and battery charging) include losses from the inverter, where not all energy sent to the battery is of high quality and technology. Yf (energy supplied to user) is the energy delivered to other users in a day, which reaches 3.25 kWh/kWp/day (Razmjoo et al., 2023). In addition, the Lu parameter is important to note because it shows that PV can provide energy to the battery until it reaches its full state (Kumar et al., 2020; Razmjoo et al., 2023).

Table 6. Performance ratio and SolFrac by PVsyst

Month	PR Ratio	SolFrac
Jan	0.720	1.000
Feb	0.700	1.000
Mar	0.663	1.000
Apr	0.619	1.000
May	0.618	1.000
Jun	0.611	1.000
Jul	0.552	1.000
Aug	0.556	1.000
Sep	0.591	1.000
Oct	0.713	1.000
Nov	0.742	1.000
Dec	0.812	1.000
Year	0.649	1.000

The annual performance ratio (PR) of the PV system reached 0.649, with monthly values ranging from 0.552 in July to 0.812 in December. Meanwhile, the Solar Fraction remained at 1.000 throughout the simulation period, indicating that the energy demand was fully satisfied by the hybrid renewable energy system. Regarding the battery storage in this hybrid system, the value in Table 7 shows the charging condition of the battery for a year in months. The upward curve is a condition where the battery is being charged by PV. The downward curve is a condition where the battery is used by the load due to decreased PV production (night condition or no sunlight). What needs to be noted is that the battery SOC level is 85%. Simply put, the Performance Ratio (PR) in Table 6 is the ratio between the final energy produced by the PV system (Final Yield) and the reference energy available based on solar radiation (Reference Yield) (Nguyen & Lauwaert, 2020). The PR value is expressed as a percentage (%), and usually in the range of 0% to 100%, although it is generally between 70% and 90% in a well-functioning PV system.

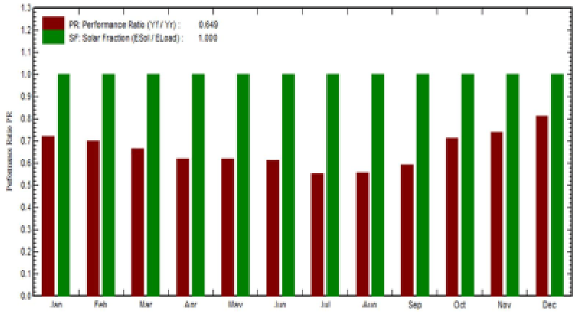


Figure 7. Performance Ratio & Solar Fraction

Performance Ratio (PR) describes how efficiently a PV system operates. A PR of 100% indicates that a system is working without losses, but this is an ideal condition that is practically unattainable due to the various losses that occur in a PV system. A PR between 70% and 90% is a common range for a well-functioning PV system, where losses that can occur include inverter inefficiency, high temperatures, cable losses, and radiation losses due to soiling. A system may not run optimally if PR is less than 70%. This could be due to improper panel placement, hardware inefficiency, shading, or inefficient energy management. Meanwhile, Solar Fraction is the ratio between the energy supplied by the PV system and the total energy demand, usually expressed as a percentage (%). Solar Fraction (SF) in Table 6 illustrates the rates of energy demand met by the PV system.

Table 7. Battery SOC condition by PVsyst

Month	U_Bat (V)	SOC Ratio
Jan	24.5	0.797
Feb	24.4	0.755
Mar	24.5	0.831
Apr	24.6	0.835
May	24.5	0.819
Jun	24.5	0.813
Jul	24.6	0.842
Aug	24.6	0.847
Sep	24.5	0.835
Oct	24.5	0.823
Nov	24.3	0.735
Dec	24.3	0.727
Year	24.3	0.805

If the Solar Fraction is 100%, it means that the PV system fully meets all the load's energy demands. However, if the Solar Fraction is less than 100%, only part of the energy demand is met by the PV, while the rest must be met by other energy sources such as batteries or generators. After conducting calculations and system analysis, it is important to understand how the methods applied in sizing the components of this hybrid system contribute to the overall performance. The calculation methods used, including the sizing analysis of the Stirling Engine Generator (SEG), photovoltaic (PV) panels, and batteries, provide a solid foundation for evaluating the results obtained.

Economic Calculation Method

The economic calculation method used in this study is based on the analysis of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), which are influenced by several key factors, including equipment costs, maintenance requirements, and fuel prices. CAPEX represents the initial investment cost required to install the hybrid system, including the purchase of equipment and installation services. This cost is typically a one-time expense, but for analysis purposes, it is amortized over the system's economic lifespan to obtain an annual value. OPEX, on the other hand, accounts for the recurring cost necessary to operate and maintain the system each year. This includes routine maintenance, spare parts replacement, labor costs, and fuel consumption, factors that can vary significantly depending on market conditions and system performance. To evaluate the overall financial viability of the hybrid system, the Return on Investment (ROI) is also calculated. ROI measures the percentage gain or loss in relation to the initial CAPEX, providing insight into how effectively the investment generates economic benefits. A positive ROI indicates profitability, while a negative ROI suggests a loss. The combination of CAPEX, OPEX, and ROI in the analysis provides a comprehensive view of the system's economic performance, helping stakeholders make informed decisions regarding its feasibility and long-term value.

RESULTS AND DISCUSSION

After the technical calculations and simulations using PVsyst have been conducted and the results obtained, as shown in Table 8, the final design can be illustrated in Figure 8. This final design serves as a reference for calculating the reduction in the economic aspects, fuel consumption, and CO2 emissions of this study.

Table 8. Equipment Sizing

No	Equipment	Sizing	Remarks
1.	Stirling Engine Generator (SEG)	1 unit	1,800 Watt
2.	Photovoltaic (PV)	5 units	5 x 350 Wp
3.	Battery Storage	1100 AH	4 days autonomy

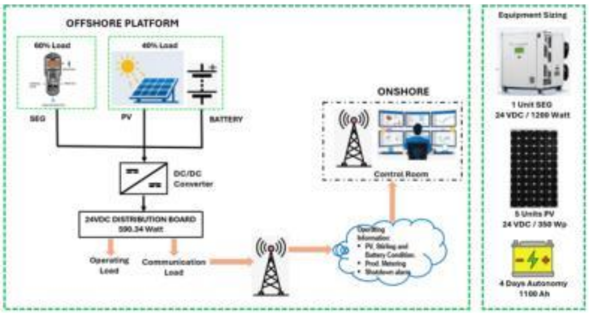


Figure 8. Final Design

The material Take-Off in Table 9 is prepared based on the final design results in Figure 8, providing a complete list of materials and components required for the project according to the technical specification and material volume needs.

Table 9. Material Take-Off

Item	Equipment	Qty
1	Stirling Engine Generator (SEG)	1
2	Isolation Switch Panel	1
3	CB BOX 24VDC	1
4	Main DCDB 24VDC & CCU	1
5	CB Box General Alarm	1
6	BATTERY 1100 AH	1
7	Battery Box 24VDC Main DB	1
8	24VDC Battery Charger	1
9	350WP Solar Panel	1
10	Electrical Cable 70mm	100 meters
11	Installation cost	LOT

Note: The material has been designed with consideration of the hazardous area

The economic analysis in Table 10 offers a detailed cost comparison between the Stirling Engine Generator (SEG) and hybrid (SEG and PV) systems. Both systems share the same installation cost (CAPEX) at USD 9,165.00, reflecting similar requirements for initial equipment and infrastructure. However, a notable difference arises in the annual maintenance cost (OPEX), the SEG system incurs USD 17,775.30, while the hybrid system requires only USD 8,887.65, marking a 50% reduction. This highlights the hybrid system's advantage in lowering maintenance expenses due to optimized load distribution between technologies. Additionally, the material cost for the TEG system is substantially higher, at USD 374,637.50, compared to the hybrid system, which only requires USD 264,092.50, saving around USD 116,585.00. This cost reduction is due to the use of PV, which incorporates more affordable and accessible materials. Regarding annual fuel costs, the SEG system incurs USD 2,634.84, while the hybrid system requires only USD 1,505.63, thanks to PV's contribution, which reduces reliance on external fuel and provides an additional savings of USD 1,129.22 per year.

In total, the combined CAPEX and OPEX for the SEG system amounts to USD 401,087.64, whereas the hybrid system is more economical at USD 274,485.77, resulting in a saving of USD 126,601.87. This analysis demonstrates that the hybrid system is a more economically viable choice, especially for long-term application in offshore environments that prioritize cost-efficiency and sustainability (Antunes et al., 2024; Lee et al., 2021).

Table 10. Economic Table

No	Description	Stirling Engine Generator (SEG)		Hybrid System		Deviation
		CAPEX	OPEX	CAPEX	OPEX	
1	Installation Cost	9,165.00		9,165.00		-
2	Maintenance Cost/Year		17,775.30		8,887.65	8,887.65
3	Material Cost	374.637,50		1.505,63		116,585.00
4	Fuel Cost/Year		2.634,84		1.505,63	1,129.22
Total		380,677.50	20,410.14	264,092.50	10,393.27	126,601.87

Note: (a) The price in US Dollars (USD), CAPEX, and OPEX price for 1 offshore platform per year

After obtaining the economic values in Table 10, Table 11 below shows the percentage of profit or loss derived from an investment compared to the initial capital invested. A positive ROI indicates that the investment yields a profit-the higher the ROI percentage, the greater the return on investment. For example, an ROI of 20% means that the investment generates a profit equivalent to 20% of the initial capital. When the ROI is 0%, it means the investment has reached the Break-Event Point, where the amount invested equals the amount returned, resulting in neither profit nor loss. On the other hand, a negative ROI indicates a loss, meaning the revenue or savings from the investment are insufficient to cover the initial capital. For instance, an ROI of -10% represents a 10% loss on the original investment. A high ROI is generally considered an indication of a profitable investment, whereas a low or negative ROI suggests the investment may be less profitable or even unprofitable, and thus may need to be reconsidered.

Table 11. Return on Investment

Parameter	Value (USD)
Initial Investment	264,092.50
Deviation (100% SEG & Hybrid)	126,601.87
Return on Investment (ROI) %	48%

In Table 11 above, it can be seen that the ROI stands at 48%, indicating that the investment is highly favourable. This level of ROI reflects a significant return relative to the initial capital, suggesting that the investment is performing well and generating substantial benefits. This information can guide decision-making regarding which energy system might be more suitable for deployment, especially in terms of economic viability and long-term operational costs. Finally, Table 12 compares two energy systems, a 100% Stirling Engine Generator (SEG) and a hybrid system integrating SEG with Photovoltaic (PV) panels. The 100% SEG system has an area of 1.25 m² and a weight of 392 kg, while the hybrid system requires a larger area of 10.96 m² but is lighter at 507 kg. That indicates that the hybrid system is structurally advantageous despite needing more installation space due to its reduced weight.

Regarding natural gas consumption, the 100% SEG system consumes 1.45 MMSCF per year, whereas the hybrid system only requires 0.84 MMSCF annually, demonstrating a significant reduction in dependence on fossil fuel due to the integration of PV. Additionally, regarding emissions, the 100% SEG system produces 0.620 tons of CO2 equivalent annually. This reduction highlights the hybrid system's effectiveness in decreasing carbon footprints and promoting environmental sustainability. Overall, the result underscores that the hybrid system not only enhances energy efficiency and reduces fossil fuel consumption but also significantly lowers greenhouse gas emissions, making it a promising solution for sustainable energy development in offshore contexts.

Table 12. Technical Data of the System and the Hybrid System

System	Area (m^2)	Weight (kg)	Number of Devices		Natural Gas Consumption (MMSCF/year)	Emissions (ton CO2 eq./year)
			PV	SEG		
100% SEG	1.25	392	0	1	1.45	0.620
100% PV	9.71	115	5	0	0	0
Hybrid	10.96	507	5	1	0.84	0.372

Existing research highlights the techno-economic advantages of integrating renewable energy sources in offshore oil and gas operations through a hybrid system that combines a Stirling Engine Generator (SEG) and photovoltaic (PV) panels. The study identifies three main areas for enhancing performance and sustainability.

First, operational optimization reduces reliance on natural gas and improves energy efficiency, resulting in significant cost savings through lower fuel and maintenance expenses. Second, technological innovation addresses solar energy variability by balancing intermittent PV output with stable SEG generation, ensuring reliable energy production and minimizing the need for complex infrastructure. Third, cost-effective CO2 reduction is achieved through an integrated monitoring and control system that enhances efficiency and extends equipment lifespan, allowing for broader application beyond offshore platforms.

Overall, hybrid systems offer clear economic advantages over traditional SEG or fossil fuel-based systems, driven by reduced fuel costs and declining PV panel prices. Although initial investments may be higher, the faster payback periods and potential for carbon credits position hybrid systems as a sustainable choice for long-term offshore energy solutions. Future research should focus on optimizing space usage, addressing weather variability, and improving smart grid connectivity for enhanced economic and operational outcomes.

CONCLUSION

The integration of a natural gas-fired Stirling Engine Generator (SEG) hybrid system with photovoltaics (PV) has proven capable of improving energy efficiency, reducing fossil fuel consumption, and lowering carbon emissions in offshore oil and gas operations. From a technical-economic perspective, the hybrid configuration demonstrates superior performance through cost savings of up to USD 126,601.87 compared to a 100% SEG system, as well as an ROI of 48%, affirming its financial viability and implementation prospects as a sustainable energy solution. Although system integration increases operational and maintenance complexity in challenging offshore environments, the potential for optimization through the development of advanced control strategies and more adaptive system integration remains significant. This study also serves as an initial comprehensive evaluation of SEG–PV integration on offshore oil and gas platforms from technical-economic and environmental perspectives, thereby providing a crucial foundation for the development of sustainable hybrid energy technologies in the offshore sector.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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