



Design and evaluation of a TEG-PV hybrid energy system for sustainable offshore oil and gas operations using PVsyst simulation

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Abstract

The rising demand for sustainable offshore oil and gas operations has accelerated the need for efficient, low-emission energy systems. Conventional fossil fuel-based systems significantly contribute to greenhouse gas emissions, underscoring the need for innovative alternatives. This study proposes and evaluates a hybrid energy system that integrates thermoelectric generators (TEGs) and photovoltaic (PV) panels to enhance energy efficiency, reduce emissions, and improve the sustainability of offshore operations. The system design utilizes both manual calculations and simulations, employing PVsyst software, to evaluate performance metrics. Results show that the TEG + PV hybrid system improves energy efficiency and reduces carbon emissions by approximately 40% compared to traditional fossil fuel systems. TEGs utilize waste heat from natural gas combustion, while PV panels capture solar energy, creating a synergistic effect that significantly reduces environmental impact. This hybrid configuration also aligns with emission reduction regulations in the oil and gas sector. Beyond environmental benefits, the hybrid system offers economic advantages. Fuel consumption and operational costs are notably reduced, with total savings in capital and operational expenditures (CAPEX and OPEX) reaching IDR 2.53 billion. These savings demonstrate the system's financial viability and support its adoption in real-world offshore applications. In conclusion, the integration of TEG and PV technologies into a hybrid energy system offers a practical and sustainable solution for offshore oil and gas operations. The system achieves emission reduction targets, enhances operational efficiency, and delivers cost savings, thereby supporting the industry's transition toward more environmentally responsible energy practices.

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INTRODUCTION

Offshore platforms still heavily rely on fossil fuels such as natural gas and diesel oil to meet their energy needs. This reliance significantly

contributes to greenhouse gas emissions [1], exacerbating global environmental issues. Although these conventional energy systems are reliable in supporting operations, long-term

dependence on fossil fuels is not a sustainable solution [2][3]. Some approaches that have been explored include the use of renewable energy sources [4][5], such as the integration of PV panels and wind turbines in offshore oil and gas operations, exploring technological advancements and their implications [6, 7, 8].

Generally, the integration of hybrid PV and wind turbine systems on offshore platforms can significantly enhance energy efficiency and reduce carbon emissions [9]. Additionally, some researchers have analyzed the advantages and challenges of integrating PV systems with diesel generators, especially in terms of energy supply stability and operational costs [10]. Thermoelectric technology (TEG), which works through the Seebeck effect, where temperature differences are converted into an electrical voltage, has not yet been widely discussed [11, 12, 13].

Several studies have explored the integration of renewable energy in offshore oil and gas operations, investigating various technological advancements and their implications. For example, Shadman et al. (2023) studied the general potential of "Offshore Renewable Energy" [14], while Solomin et al. [6] conducted a more detailed study on "Offshore PV and Wind-based Energy Generation," focusing on environmentally friendly power generation for offshore platforms. Other relevant studies on renewable energy in offshore platforms and their environmental impacts include those by Cherepovitsyna et al. [15], Serra et al. [16], Cherepovitsyn et al. [17], Li et al. [18], and Matheus et al. [19]. Thermoelectric technology is commonly used on offshore oil and gas platforms, yet it has not been widely covered in research journals. Studies on Thermoelectric power generators are limited, primarily confined to laboratory tests or non-commercial applications. Among the limited research, Jouhara et al. [12] discussed thermoelectric power generation and its applications in their work, "Thermoelectric Generator (TEG) Technologies and Applications." This study aims to hybridize solar power (PV) with a Thermoelectric Generator (TEG) as a solution for environmentally friendly power generation on offshore platforms. Although no detailed studies have been conducted on this specific hybrid approach, several journals on hybrid technologies and energy storage, such as those by Yimen et al., Igogo et al., Wang et al., and Lee et al., have published relevant research. [20, 21, 22, 23], provide useful theoretical references. While this study does not thoroughly detail the techno-economic aspects and considerations for hazardous areas, such as "Protection against

Explosions," initial calculations have been performed to serve as a foundation for future research. This enables the study to serve as a reference point for more in-depth investigations. Theoretical insights into the techno-economic aspects of renewable energy can be found in the works of Chudy-Laskowska et al., Yimen et al., and Faturachman et al. [3], [20], [24], while Brkić et al. address protection against explosions [20].

Figure 1 illustrates the schematic combination of these technologies, which is expected to significantly improve energy efficiency and reduce the carbon footprint of offshore oil and gas operations [25]. With this approach, the integration of PV and TEG can become a strategic solution for energy sustainability in the oil and gas sector, addressing current environmental and economic challenges [26].

In this context, a significant research gap exists regarding the limited exploration of hybrid systems that combine PV and TEG technologies for offshore oil and gas operations. While the integration of PV with wind turbines and diesel generators has been widely studied, there is still a lack of research focusing on the synergistic potential of PV and TEG systems, particularly under the challenging environmental conditions of offshore platforms. This study addresses this gap by developing a hybrid PV-TEG system that enhances energy efficiency and reduces carbon emissions on offshore platforms. Through PVsyst simulations and manual calculations, the system demonstrates the potential for OPEX and CAPEX savings of up to IDR 2,532,269,888, as well as a 40% reduction in fuel consumption.

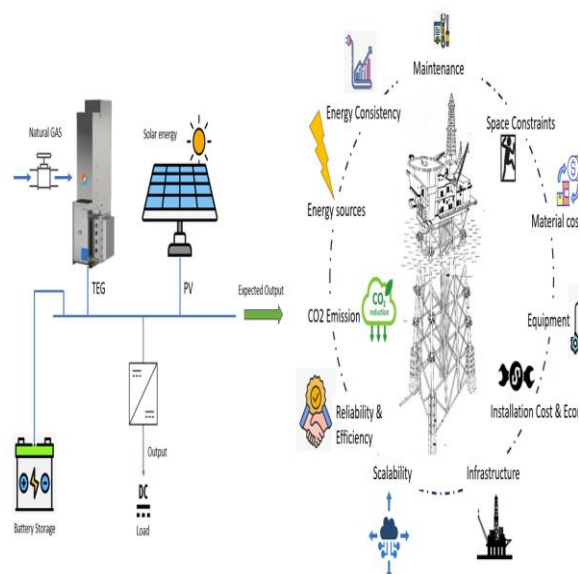


Figure 1. Hybrid output

The uniqueness of this research lies in the integration of thermoelectric technology, typically used as a standalone generator, with solar energy for offshore operations. This study focuses on adapting the system to address environmental challenges by utilizing thermoelectric energy at night and solar energy during the day, thereby creating a more efficient solution. It is expected to reduce dependence on fossil fuels, lower carbon emissions, and enhance operational efficiency. Although techno-economic aspects are not explored in depth, these findings provide an initial insight into the system's feasibility while opening opportunities for further research. The primary objective of this study is to introduce and evaluate a hybrid PV-TEG system design that not only can reduce carbon emissions but also achieve more cost-effective operations through reduced natural gas consumption and maintenance needs, contributing to a more sustainable and economical energy solution for offshore oil and gas operations [20][24].

MATERIAL AND METHOD

In this study, the equipment has been designed with careful consideration of the hazardous conditions present on the offshore platform. The TEG (Thermoelectric Generator) is 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 Ex e mb II C T6 Gb, and additionally, the battery is put in an Ex e box [27, 28, 29, 30]. The designed PV-TEG hybrid system integrates photovoltaic (PV) panels and thermoelectric generators (TEG) to operate optimally under various environmental conditions on offshore platforms. PV panels effectively generate energy during the day, while TEG utilizes heat from natural gas combustion in wells, ensuring continuous operation even in adverse weather conditions or at nighttime. The system is equipped with energy storage batteries that store excess energy from PV and distribute it when PV output decreases or extreme weather conditions occur, thereby maintaining a stable power supply. This approach ensures the system operates reliably, reducing dependence on fossil fuels and enhancing resilience to environmental challenges.

Concept Design

The proposed hybrid system design integrates a 100W TEG model 1120, commonly used to supply electrical energy on offshore platforms, with a 350Wp monocrystalline PV,

details of which can be seen in Figure 2 and Table 1.

This system is designed to allow the TEGs to function during adverse weather conditions, when sunlight intensity is low, while the PV panels contribute during sunny weather. Combining these two technologies aims to increase energy efficiency, ensure a reliable energy supply, and reduce dependence on fossil fuels. Figure 3 illustrates the proposed hybrid system design, showing the interaction between TEGs and PV panels in creating a more efficient, sustainable, and environmentally friendly energy solution that enhances system resilience and optimizes overall performance.

To ensure stable energy availability, the system is equipped with batteries as an energy storage device. These batteries serve as a backup when one of the main generators cannot meet the energy needs. With this storage system, the energy produced by both TEGs and PV panels can be stored and used when needed, increasing the flexibility and resilience of the system [31, 32, 33]. A battery storage system, in general, is shown in Figure 4.



Thermoelectric (TEG)[29] Photo Voltaic (PV) [28]

Figure 2. Hybrid Material

Table 1. Material Data Specification

Material Type	Thermoelectric	Photo Voltaic
Type	1120	Monocrystalline
Voltage	24 VDC	24 VDC
Rated Power	100 Watt	350 Wp
Dimension	658 x 801 mm	1,972 x 987 mm
Natural gas	8.8 m^3 /days	NO

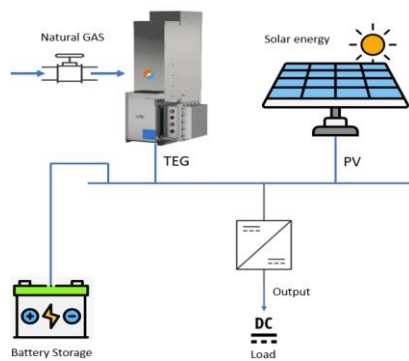


Figure 3. Hybrid System PV and TEG

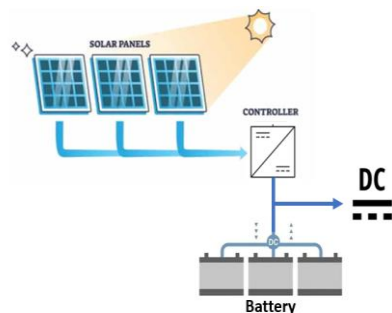


Figure 4. Battery Storage

Calculation Method

The sizing calculation for this hybrid system aims to determine the optimal capacities of the main components, including Thermoelectric generators (TEGs), PV panels, and batteries. The system is designed with a configuration that allocates 60% of the power contribution to TEGs and 40% to PVs and batteries. TEGs provide the majority of energy supply to ensure stability, especially when solar radiation is low or absent. Meanwhile, PVs generate 40% of the energy demand, with sizes adjusted through PVsyst simulation. This contribution from PVs helps reduce fuel consumption by TEGs, thus significantly reducing CO₂ emissions [16][34].

The batteries serve to store excess energy from PVs and provide power when PV production decreases, ensuring a continuous energy supply and optimal efficiency [23]. 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. After obtaining the load list above, the capacity of the TEGs can be calculated. The sizes of the TEGs are shown in Table 3.

The sizing calculation of the battery and PV panel system is performed using PVsyst software [35][36] as shown in Figure 5. It shows that the PV and battery configuration manages 40% of the load, as shown in Table 2, and the battery autonomy is 4 days.

Table 2. Load Assumption

No.	Equipment Name	Load (W)
A	SSS Panel	373.85
B	Radio Communication	15
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]	547.18
H	Floating current to maintain a full charge	43.16
I	TOTAL [I = G + H]	590.34

Table 3. TEG Sizing

Description	Value	Unit	Remarks
A Power of TEG			
A.1 Rated Power	100	Watt	
A.2 Nominal Voltage	24	VDC	
A.3 Rated Power@ 35°C Temperature	97.5	Watt	Note: 1
B Consumer Load			
B.1 Load List * 60%	354.204	Watt	Table 2
°C TEG Required			
C.1 Round-Up	3.6	Units	B.1 / A.3
TEG Installed	4	Units	

Note: Rated Power at 35 °C Temperature, as recommended by the vendor.

In addition to the equipment sizing calculations above, hybrid system performance simulations are performed with PVsyst software to evaluate the performance of PV systems [35, 37, 38]. Table 4 shows the points, which are the factors calculated in the performance evaluation using PVsyst. The results from these simulations provide valuable insights into optimizing the hybrid system's efficiency and reliability, ensuring energy sustainability for offshore operations under various environmental conditions.

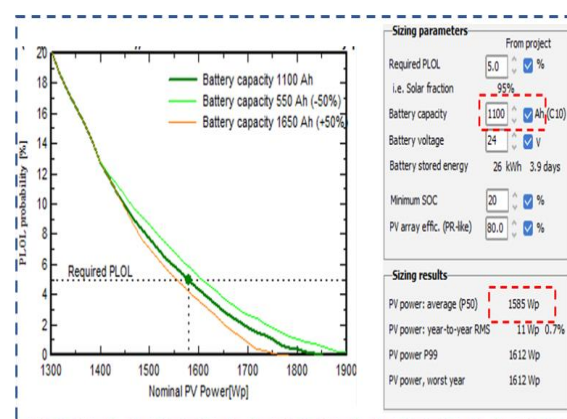


Figure 5. Battery and PV Sizing Calculated by PVsyst

Table 4. Parameter of Calculation

No	Parameters	Value	Remarks
A	Orientation		
1	Tilt	21.5 degree	Est Kalimantan
2	Azimuth	0 degree	
B	User needs		
1	Daily Load	237 W/app	40% Load
2	Daily Use	24 h/day	
C	Detailed 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	Array Design		
1	PV series	1 ea	
2	Strings	5 ea	Parallel
F	Storage		
1	Type	Lead-acid	
2	Manufacturer	Sonnenschein	
3	Sort battery	Voltage	
4	Voltage/cell	2 V	
5	Capacity	680 Ah	
6	Temperature	Avg ambient	
7	Fixed temp.	35 °C	Ambient temp

The system's performance is assessed based on several key points: 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. PR describes the ratio between the energy generated and its ideal energy potential, indicating how effectively the system operates under real-world conditions.

The SOC (State of Charge) [39]

The condition of the battery throughout the year is also a key metric. It indicates the charge and discharge rates of the battery during operation, reflecting the system's ability 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 numerical form are presented in Tables 5, 6, and 7.

In Table 5, the energy produced per day is shown, along with values representing the energy generated and losses over 12 months. **Lu** (unused energy) refers to the energy produced by the PV system, but it cannot be stored in the battery due to its full capacity. This energy cannot be utilized

when there is insufficient electricity demand from the load. **Lc** (collection loss) includes losses that occur in the PV array, such as thermal losses, cable losses, and other factors [35][40]. Next, **Ls** (system losses and battery charging) include losses from the inverter, where not all the energy sent to the battery can be stored due to inefficiency [35]. Battery charging efficiency is affected by battery quality and technology. **Yf** (energy supplied to the user) is the energy delivered to the user in a day, reaching 3.25 kWh/kWp/day [35]. In addition, the **Lu** parameter is noteworthy because it indicates that PV can supply energy to the battery until it reaches its fully charged state [35][37].

Table 5. Energy generated per installed capacity

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	1.91	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 6. Performance ratio and SolFrac

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

Table 7. Battery SOC condition

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

Regarding the battery storage in this hybrid system, Table 7 presents the charging conditions of the battery over one year, expressed in months. The upward value is a condition where PV is charging the battery. The downward value is a condition where the battery is discharged by the load due to decreased PV production (in night conditions or with no sunlight). What needs to be noted is that the battery SOC condition does not reach the specified lower limit, which is 20%. It can be seen that the lower limit on the curve is above 55%. The PV is also capable of charging the battery up to a SOC level of 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) [41]. The PR value is expressed as a percentage (%), typically ranging from 0% to 100%, although it is generally between 70% and 90% in a well-functioning PV system [35].

$$PR = \frac{Y_f}{Y_r} \quad (1)$$

Performance Ratio (PR) describes how efficiently a PV system operates. A PR of 100% indicates that a system is operating without losses; however, this is an ideal condition that is practically unattainable due to the various losses that occur in PV systems [35]. A PR between 70% and 90% is a typical 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.

$$PR = \frac{Y_f}{(Lu + Lc + Ls + Yf)} \quad (2)$$

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, the Solar Fraction is the ratio of the energy supplied by the PV system to the total energy demand, usually expressed as a percentage (%).

$$SF = \frac{E_{User}}{E_{Load}} \quad (3)$$

The Solar Fraction (SF) in Figure 7 illustrates the percentage of energy demand met by the PV system [35]. If the Solar Fraction is 100%, 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 system, while other energy sources, such as batteries or generators, must meet the rest.

In this study, the State of Charge (SOC) calculation uses the Voltage-based Method, which relies on the relationship between battery voltage and SOC. This method involves three primary parameters: V_{batt} , the current battery voltage; V_{min} , the minimum voltage considered as SOC 0%; and V_{max} , the maximum voltage considered as SOC 100%.

$$SOC = \frac{V_{batt} - V_{min}}{V_{max} - V_{min}} \times 100\% \quad (4)$$

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 TEGs, PV panels, and batteries, provide a solid foundation for evaluating the results obtained.

Hybrid Scenario

Following the initial simulation, where PVsyst's recommendation regarding the number of PVs was taken as a reference and referred to as Scenario 1, the following simulations will be conducted with different scenarios. In scenario 2, the units of PVs are reduced, assuming that the energy shortage will be met by battery storage. Again, the following simulation, scenario 3, will be conducted by increasing the number of PVs with the assumption that it can improve the reliability of the hybrid system. However, the hybrid configuration is still maintained, i.e., 60% TEG and 40% PV. Various PV sizes will be analyzed to evaluate their impact on energy efficiency, total energy generated, and fuel consumption reduction. These simulations aim to determine the optimal size of a PV system. Table 8 below describes the equipment sizing for scenarios 1, 2, and 3.

Tables 9, 10, and 11 display the performance values for each scenario. These system performance values are obtained by breaking down the Solar Fraction, Performance Ratio, and State of Charge for each scenario using the previously explained method.

Table 8. PV Hybrid Scenario

Scenario	PV Sizing	Unit	Remarks
1	PV Sizing	5	PVsyst
2	PV Sizing	3	The energy shortfall
3	PV Sizing	7	High reliability

Table 9. Solar Fraction (SF) values

Month	Scenario 1	Scenario 2	Scenario 3
January	1	0.7	1
February	1	0.62	1
March	1	0.72	1
April	1	0.78	1
May	1	0.76	1
June	1	0.74	1
July	1	0.88	1
August	1	0.96	1
September	1	0.72	1
October	1	0.66	1
November	1	0.58	1
December	1	0.52	1

Table 10. Performance Ratio (PR) values

Month	Scenario 1	Scenario 2	Scenario 3
January	0.72	0.88	0.54
February	0.7	0.76	0.52
March	0.68	0.78	0.48
April	0.62	0.82	0.44
May	0.62	0.8	0.44
June	0.6	0.74	0.42
July	0.52	0.8	0.38
August	0.52	0.86	0.38
September	0.58	0.74	0.4
October	0.74	0.84	0.54
November	0.72	0.82	0.62
December	0.8	0.8	0.58

Table 11. State of Charge (SOC) values

Month	Scenario 1	Scenario 2	Scenario 3
January	0.797	0.366	0.836
February	0.755	0.354	0.834
March	0.831	0.340	0.847
April	0.835	0.349	0.842
May	0.819	0.368	0.837
June	0.813	0.381	0.838
July	0.842	0.413	0.844
August	0.847	0.394	0.846
September	0.835	0.383	0.846
October	0.823	0.347	0.836
November	0.735	0.339	0.823
December	0.727	0.326	0.841

RESULT AND DISCUSSION

The calculation results of the *Solar Fraction* (SF) presented in Table 9 and the *State of Charge* (SOC) in Table 11 indicate that, among the three scenarios, Scenario 2 has the poorest performance. This is due to its SF value being less than 1, meaning that the energy generated by the PV is insufficient to meet the system's load requirements, and its SOC value is below 40%, indicating that the PV cannot charge the battery optimally. This condition is especially evident when solar intensity is low in January, October, November, and December. For more details, refer to Figures 6 and 7.

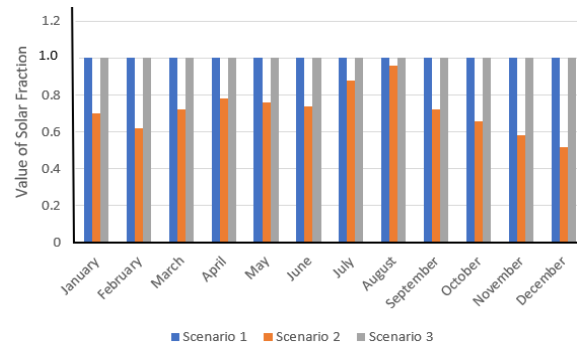


Figure 6. Comparison Scenario (SF)

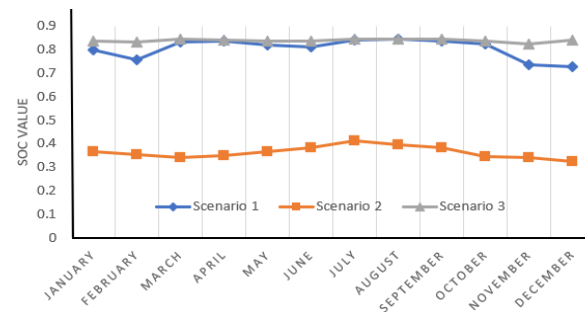


Figure 7. Comparison Scenario (SOC)

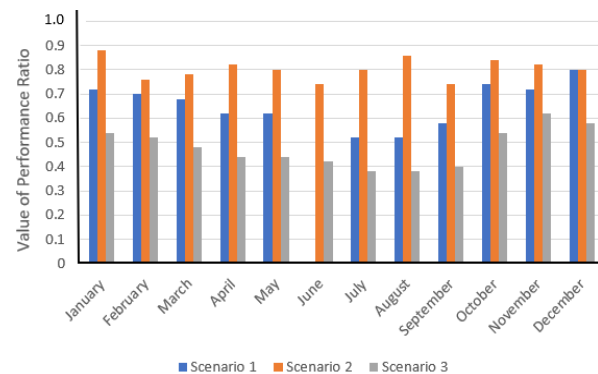


Figure 8. Comparison Scenario (PR)

The results of the calculations in Table 10, as shown in Figure 8, indicate that Scenario 3 has the lowest value because the energy produced by the PV panels exceeds the system's needs, particularly in July, August, and September, when solar intensity is high. On the other hand, Scenario 1, as illustrated in Figures 6, 7, and 8, is the most effective because it balances the energy produced by the system with the energy required for operation. Based on that, the results are listed in Table 12.

After the technical calculations and simulations using PVsyst have been conducted and the results obtained, as shown in Table 12, the final design can be illustrated in Figure 9. This final design serves as a reference for calculating the reduction in fuel consumption, CO₂ emissions, and the economic aspects of this study.

Table 12. Equipment Sizing

No	Equipment	Sizing	Remarks
1.	TEG	4 Unit	4 x 97.5 Watt
2.	PV	5 Unit	5 x 350 Wp
3.	Battery	1100 AH	4 Days Autonomy

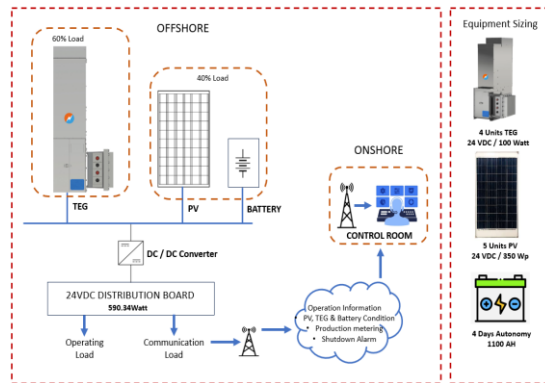
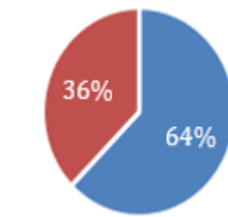


Figure 9. Final Design

Table 13 and Figure 10 illustrate a detailed comparison of the effects of the hybrid system configuration on natural gas consumption and carbon emissions. The analysis indicates that implementing this hybrid system, despite requiring a larger installation area, can achieve a 40% reduction in natural gas fuel consumption. This improvement is significant for offshore operations, as it reduces dependence on fossil fuels and enhances energy efficiency.

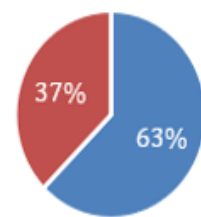
In addition, reducing natural gas consumption directly contributes to lowering carbon emissions by up to 40%, making the hybrid system a more environmentally friendly choice. These findings align well with the sustainability goals of future offshore platforms, highlighting the potential of hybrid PV and TEG systems.

Fuel Consumption



■ TEG 100% ■ Hybrid

Emissions



■ TEG 100% ■ Hybrid

Figure 10. Comparison of Fuel Consumption vs Emissions

This solution supports operational efficiency and promotes a greener, more sustainable approach in offshore energy systems.

From an economic perspective, the hybrid system design, which combines PV panels and a TEG, proves to be cheaper than using a 100% TEG system, as shown in Table 14. The main cost savings come from the significant reduction in fuel consumption, as the hybrid system requires less natural gas fuel than the full TEG. Additionally, the lower price of PV panels compared to TEG units also contributes to lower initial costs.

Another economic advantage is the lower maintenance costs of the hybrid system, as it eliminates the need to maintain the fuel gas system, which typically requires regular maintenance and incurs additional costs. Thus, the hybrid design is not only more efficient in terms of energy and emissions but also offers a more cost-effective solution in the long term [20, 24, 42].

Table 13. Technical Data of the TEG System and the Hybrid System

System	m ²	Kg	Devices		Gas (GJ/year)	Emissions (CO ² ton/year)
			PV	TEG		
TEG	4.6	1508	0	7	793.68	990.45
Hybrid	14.6	1050	5	4	453.53	565.97

Table 14. Economic Table

Description	TEG		Hybrid System		Deviation
	CAPEX	OPEX	CAPEX	OPEX	
Installation	146,640,000		146,640,000		-
Maintenance Cost/year		284,404,777		142,202,388	142,202,389
Material Cost	5,944,200,000		3,572,200,000		2,372,000,000
Fuel Cost/year		42,157,500		24,090,000	18,067,500
Total	6,090,840,000	326,562,277	3,718,840,000	166,292,388	2,532,269,889

Note: (a) The price in Indonesian Rupiah (IDR); (b) OPEX price for 1 offshore platform per year.

Existing research provides comprehensive insights into integrating renewable energy sources in offshore oil and gas operations. The study identifies three key areas to improve system performance and sustainability. These areas focus on operational improvements, technological innovations to maximize energy efficiency, and minimizing CO₂ emissions [19].

Firstly, Energy Use Optimization through Hybrid System Integration. The core of this design lies in the hybrid system that combines TEGs with PV panels. By strategically integrating this system, energy consumption can be optimized using renewable energy sources. This integration ensures a reliable energy supply, reduces dependence on natural gas, and improves overall energy efficiency. Secondly, Evaluation of Hybrid System Efficiency in Offshore Conditions. Solar energy potential varies significantly in offshore environments, and weather conditions can limit solar radiation. Therefore, the energy generation performance of these systems must be supported by more stable energy sources. The combination of TEG and PV can ensure system resilience in offshore environments, increase the reliability of energy generation, and reduce the need for complex infrastructure. Thirdly, the Development of an Integrated Monitoring and Control System. To fully utilize the potential of hybrid systems, a robust monitoring and control system is essential. Generally, a photovoltaic and Thermoelectric hybrid energy system for offshore oil and gas operations offers significant improvements in energy efficiency, reduces gas consumption, and lowers CO₂ emissions [9][43], making it a superior alternative for sustainable energy generation in offshore environments. A Hybrid TEG system with renewable energy sources such as PV panels has the potential to be applied not only in offshore oil and gas platforms but also in other systems [12].

This research underscores the necessity for sustainable energy solutions that minimize fossil fuel dependence while maintaining reliability. However, challenges remain, including offshore weather variability, space constraints, and integration with existing infrastructure. Further studies are needed on long-term cost management. Despite relying on simulations, this study demonstrates the potential of PV-TEG hybrid systems for enhancing offshore energy efficiency and sustainability. Future research should focus on resolving these challenges, advancing technologies, and optimizing space usage, as well as improving connectivity through smart grid and predictive maintenance technologies [11][44] to enhance energy

efficiency, optimization [45][46], and security. From an economic perspective, the hybrid system offers fast investment recovery through fuel savings and lower maintenance costs. The declining cost of PV panels further enhances its long-term cost-effectiveness, providing both environmental and economic benefits that boost industry competitiveness.

CONCLUSION

The analysis of a hybrid TEG system, which utilizes natural gas and photovoltaics (PV), demonstrates significant improvements in energy efficiency and carbon emission reduction for offshore oil and gas operations. By integrating PV with TEG, the system reduces dependence on fossil fuels while enhancing energy stability and promoting sustainability. However, the complexity of hybrid integration poses operational challenges, particularly in maintenance and management. Economically, reduced natural gas consumption lowers operational costs, while the affordability of PV panels minimizes initial investment and maintenance expenses. A key deviation from prior studies is the unexpected complexity in integration, influenced by system configuration and environmental factors. Future research should optimize system integration and explore advanced control strategies to enhance efficiency and reliability in offshore environments.

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