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# Hybrid Energy Solutions for Sustainable Offshore Oil and Gas Operations: Leveraging Thermoelectric, Solar, and Wind Potential

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### Abstract

The transition towards sustainable offshore oil and gas operations is increasingly important given the declining conventional energy reserves and growing environmental concerns. This research developed a concept design to enhance sustainability in offshore operations by integrating local solar and wind energy sources. The proposed hybrid system combines solar energy systems and wind turbines with traditional Thermoelectric Generators (TEGs), which have traditionally relied on natural gas. The study found that incorporating these renewable energy sources into the system significantly reduces carbon emissions, lowers dependency on fossil fuels, and improves overall operational efficiency. The main conclusion of this research is that integrating local renewable energy sources into offshore operations mitigates environmental impact, offers long-term cost savings, and enhances energy security. This framework provides practical solutions for the energy sector's transition towards greener, more resilient offshore operations.



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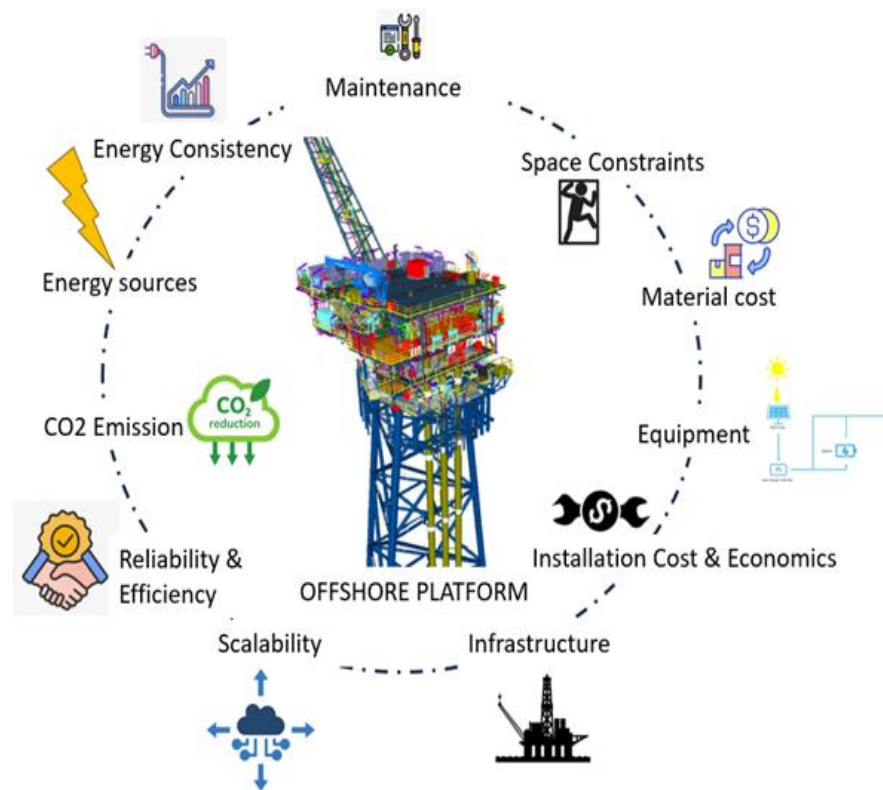
## 1. Introduction

The global energy landscape is transforming significantly as industries seek to balance economic growth with environmental sustainability [1–3]. Traditional energy sources, particularly fossil fuels, have long been the cornerstone of industrial operations, including offshore oil and gas. However, the growing concerns about climate change, resource depletion, and environmental impact have intensified the need for alternative energy solutions [4–6].

Renewable energy, with its ability to provide cleaner and more sustainable power, has emerged as a critical focus for industries looking to reduce their carbon footprint and enhance energy resilience [7]. Offshore oil and gas

operations, once heavily reliant on fossil fuels, are now exploring ways to incorporate renewable technologies into their energy mix [8].

In response to these challenges, Zereskian is placing a growing emphasis on integrating renewable energy sources, such as solar and wind power, into offshore oil and gas operations [9]. This integration offers a promising solution to improving the sustainability of operations while reducing dependence on dwindling fossil fuels. To transition to sustainable offshore practices, a comprehensive understanding of the potential and feasibility of utilizing local renewable energy resources is crucial [10, 11].



**Figure 1.** Point of scoring and evaluation.

As this shift gains momentum, exploring and building on existing research in this sector is important. Igogo et al. [12] outline the challenges, opportunities, and enabling approaches for integrating renewable technologies into mining operations, emphasizing the need for innovative solutions to overcome technical barriers, optimize costs, and maximize environmental benefits. These insights are also relevant to the oil and gas industry.

Figure 1 illustrates the points considered in determining the energy source used on an offshore platform. These include factors such as energy consistency, carbon emissions, operational and installation costs, reliability, and the feasibility of integrating the system with existing infrastructure. These points are crucial in selecting the most appropriate energy system for implementation on the platform [13].

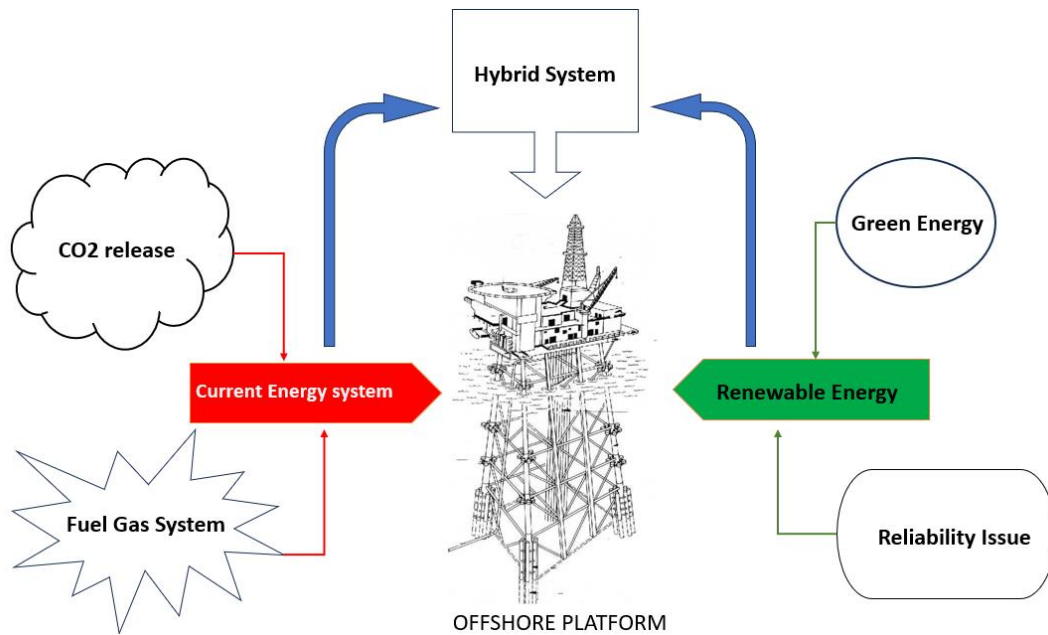
Several studies have explored the integration of renewable energy into offshore oil and gas operations, examining various technological advancements and their implications. For instance, Maienza et al. [14] demonstrated the feasibility of using offshore wind farms to power oil platforms, highlighting significant potential for carbon emission reductions. Similarly, Wang et al. [15] examined the challenges of solar energy integration in offshore operations, especially in areas with fluctuating weather conditions.

Focusing on economic aspects, Ekechukwu et al. and Braga et al. [16, 17] analyzed the cost-effectiveness of renewable energy integration in offshore oilfields. Additionally, Zhang et al. and Sharif et al. [18, 19] explored the environmental benefits, emphasizing the reduction of ecological footprints.

Furthermore, the global energy landscape transforms significantly as energy demand increases, driven by rapid population growth, industrial development, and technological advancements [20]. This shift necessitates a deeper focus on techno-economic analyses to ensure that emerging energy solutions are technically feasible and economically viable, supporting sustainable development on a global scale [21].

Offshore oil and gas operations have long been integral in meeting the world's energy needs. Jouhara et al. and Sanin-Villa [22, 23] studied related Thermoelectric Generators (TEGs) that convert heat directly into electrical energy through the Seebeck effect. In this phenomenon, a temperature difference across has long been used as an energy source on offshore platforms, utilizing natural gas to generate electricity through the thermoelectric effect.

Although TEGs offer a relatively clean solution compared with other fossil fuels, depleting conventional oil and gas reserves continues to present a major challenge.



**Figure 2.** Energy system at the offshore platform.

Therefore, adopting more sustainable and comprehensive practices through renewable energy is important. Finally, the study by Solomin et al. [24] provided insight into the practical challenges of implementing these technologies in real-world scenarios, especially in remote offshore locations.

While existing literature provides a strong foundation on the benefits and challenges of integrating renewable energy into offshore oil and gas operations, it often lacks practical insights into real-world applications. To address this gap, this research proposes a new concept design for sustainable offshore oil and gas operations [25]. It effectively utilizes local solar and wind energy potential [20] and combines it with a hybrid system featuring TEG. The main objective of this study is to develop a practical and efficient framework that can be applied to offshore operations and contribute to achieving energy sustainability in the sector [26]. Moreover, this study underscores the importance of evaluating the environmental impacts of renewable energy implementation in offshore operations, including carbon emission reductions and improved energy efficiency, to ensure that proposed solutions are both energy-sustainable and environmentally friendly.

## 2. Materials and Methods

Offshore platforms have historically relied on fossil fuels, considered reliable energy sources for oil and gas operations, as illustrated in Figure 2. However, renewable energy sources such as wind and solar have great potential to reduce carbon footprint, although they depend highly on weather conditions [27–29]. A hybrid

system that combines conventional and renewable energy is an effective solution [30, 31], utilizing renewable energy to reduce dependence on fossil fuels [32, 33] while ensuring continuity of operation through fossil energy support when renewable sources are insufficient [34, 35].

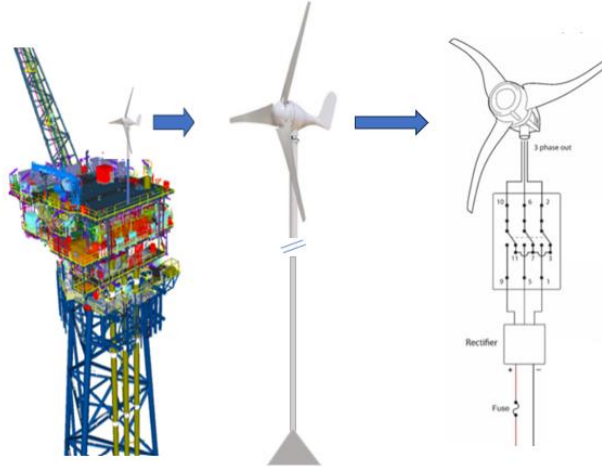
TEG, photovoltaic (PV) panels, and wind turbines are the main materials in this energy system concept. TEGs, which convert thermal energy from natural gas into electricity through the thermoelectric effect, are employed to provide a stable energy supply. PV panels harness sunlight to generate electricity directly, offering a renewable energy source that reduces reliance on fossil fuels. Wind turbines convert the wind's kinetic energy into electrical energy, further contributing to the renewable energy mix. This concept will be implemented on offshore platforms in east Kalimantan, Indonesia, to leverage the strengths of each technology, enhancing energy efficiency and reducing the carbon footprint. As shown in Figures 3, 4, 5, and Tables 1, 2, and 3, the installation and specifications of the materials used in this energy system are detailed.

In this study, the equipment has been designed with careful consideration of the hazardous conditions present on the offshore platform. The TEG is suitable for hazardous areas, classified as Class I, Div 2, Group D, with a temperature rating of T3. The PV system complies with the ATEX code Ex II 2 G Ex e mb II C T6 Gb. Additionally, the wind turbine is a non-hazardous only marine type. It will be positioned at the edge of the platform, outside of Zone 2, which is designated as a safe area. To enhance

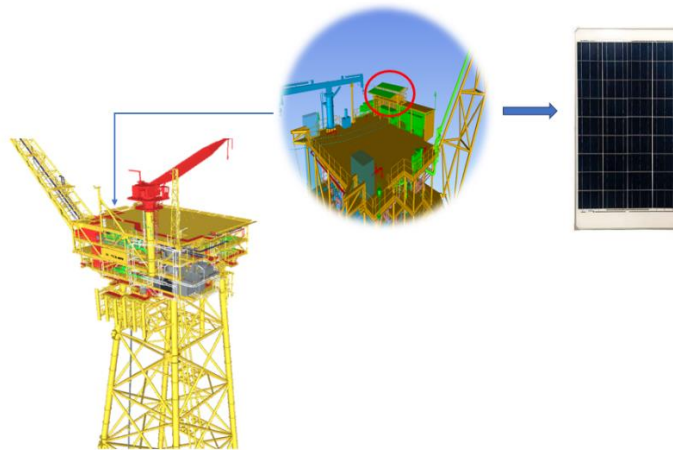
safety, gas detectors will also be installed as an additional mitigation measure.

The selection of the best energy system for an offshore platform can be facilitated by a quantitative assessment that compares the current energy system with the integration of solar and wind energy [36]. Scoring on

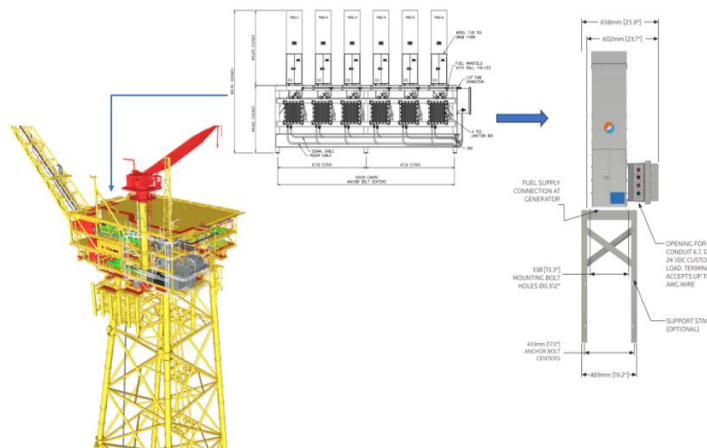
parameters such as energy consumption, renewable energy contribution [37], carbon emissions [38], operational costs [39], constructability and energy efficiency provide a clear picture of the performance of each system [40]. Each criterion is evaluated based on a defined scale, where lower energy



Figures 3. Illustration of wind turbine installation.



Figures 4. Illustration of PV installation.



Figures 5. Illustration of TEG installation.

**Table 1.** Wind turbine specification [41].

Wind Turbine	Specification
Model	WTD 1000-48
Rotor Dimension	2.7 m
Nominal Volt & Watt	48 V / 1000 W
Start-up Wind speed	2.5 m/s
Rated Wind Speed	12.5 m/s

**Table 2.** PV specification [42].

Photo Voltaic (PV)	Specification
Solar cell type	Mono Crystalline
Dimension	1,972 x 987 mm
Nominal Volt	24 VDC
Rated Power	350 Wp
Efficiency	18.2%
Part Number	SPEX 350-24
Weight	23 Kg

**Table 3.** TEG specification [43].

Thermoelectric Generator (TEG)	Specification
Model	1120
Dimension	658 x 801 mm
Nominal Volt	24 VDC
Rated Power	100 Watt
Fuel (Natural gas)	8.8 m <sup>3</sup> /days
Weight	130 Kg

**Table 4.** Scoring remarks.

Score	Narrative	Remarks
1	Very poor	Efficiency is very low, renewable energy contribution is minimal, carbon emissions are high, operational costs are high, and technology integration is poor.
2	Poor	Efficiency is low, renewable energy contribution is low, carbon emissions are high, operational costs are high, and technology integration is lacking.
3	Fair	Efficiency is adequate, renewable energy contribution is fair, carbon emissions are acceptable, operational costs are reasonable, and technology integration is basic.
4	Good	Efficiency is above average, renewable energy contribution is significant, carbon emissions are low, operational costs are efficient, and technology integration is good.
5	Very good	Efficiency is very high, renewable energy contribution is very significant, carbon emissions are very low, operational costs are very efficient, and technology integration is advanced.

consumption and carbon emissions receive higher scores, reflecting better sustainability. Similarly, systems demonstrating greater renewable energy contributions and lower operational costs are rated more favorably. Constructability and energy efficiency are assessed to ensure the feasibility and effectiveness of the system in real-world applications. Table 4 describes the scores used in system selection.

### 3. Results and Discussion

A comparison of current energy systems, such as TEGs, with PV and wind energy systems, as well as hybrid systems, is detailed in Table 5. This table describes the advantages and disadvantages of each system and facilitates the evaluation of performance, cost, and environmental impact.

The current focus is on selecting the best energy system for offshore platforms. TEG is the current energy source, along with solar, wind, and hybrid systems. Table 6 shows the scores of each system based on the scoring system outlined in Table 4.

After obtaining the scoring results, it was found that the hybrid system combining solar energy and TEG achieved the highest scores compared to other energy systems. This result directly addresses the research question by demonstrating that the hybrid approach offers significant advantages in several key areas.

The main discovery is that the combination of solar energy and TEG enhances energy efficiency by optimally utilizing both sources to improve overall performance.

**Table 5.** Comparison of current energy system (TEG) and Opportunity of PV, wind energy, and hybrid systems.

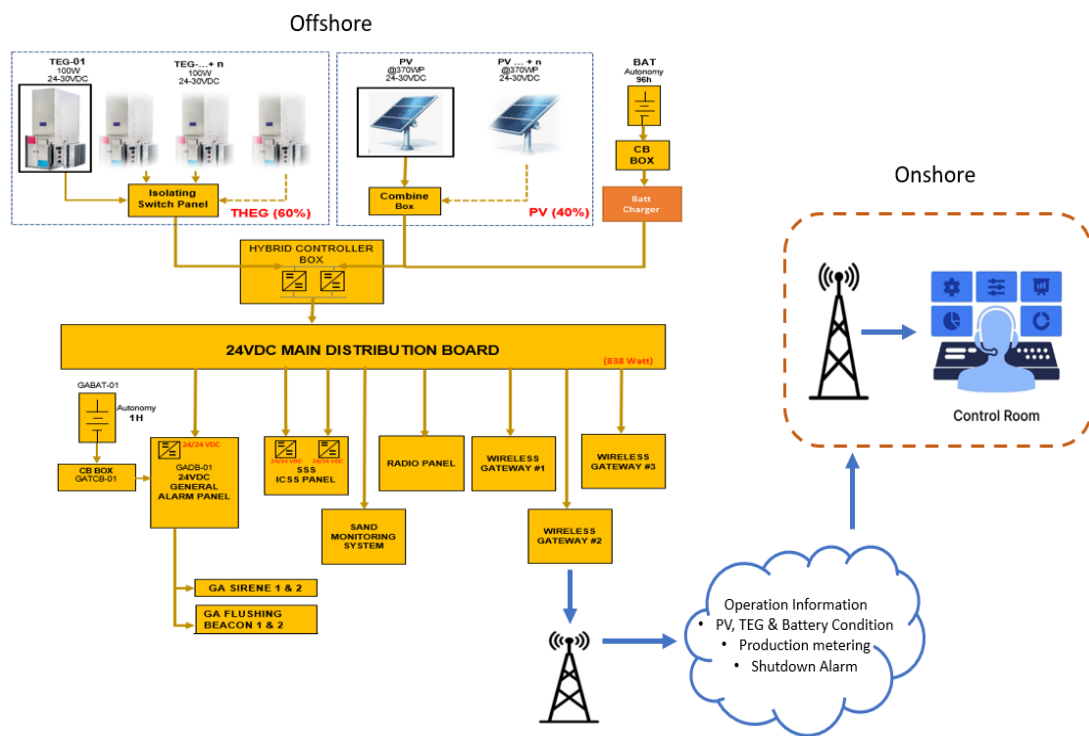
Parameter	TEG with Natural Gas	Solar PV Energy	Wind Energy	Hybrid TEG and PV	Hybrid TEG and Wind	PV and Wind
<b>Energy Source</b>	Gas (from offshore wells)	Solar radiation	Wind movement	Gas + Solar radiation	Gas + Wind movement	Solar + Wind
<b>Carbon Emissions</b>	Medium (depends on gas combustion)	Zero	Zero	Low (reduced emissions with PV)	Low (reduced emissions with Wind)	Zero
<b>Operational Reliability</b>	High (continuous with stable gas supply)	Moderate (dependent on weather)	Moderate (dependent on wind consistency)	Very High (improved reliability with PV support)	Very High (improved reliability with Wind support)	High (good reliability combine resources)
<b>Energy Output Consistency</b>	Consistent (with gas supply)	Intermittent (varies with sunlight)	Intermittent (varies with wind conditions)	More consistent (PV supports during gas shortages)	More consistent (Wind supports during gas shortages)	More consistent (both complement each other)
<b>Scalability</b>	Medium	High (scalable with more panels)	High (scalable with more turbines)	High (scalable with additional TEG and PV)	High (scalable with additional TEG and Wind)	High (scalable with additional PV and Wind)
<b>Infrastructure Required</b>	Gas pipelines, TEG modules, power converters	Solar panels, energy storage systems	Wind turbines, energy storage systems	Gas pipelines, TEG modules, solar panels, inverters	Gas pipelines, TEG modules, wind turbines, energy storage system	Solar panels, wind turbines, energy storage systems
<b>Installation Cost</b>	Medium	High (initial cost, decreasing over time)	High (initial cost, decreasing over time)	Higher (cost of combining systems)	Higher (cost of combining systems)	Higher (cost of combining systems)
<b>Long-term Cost Efficiency</b>	Medium (depends on gas price)	High (lower operational costs over time)	High (lower operational costs over time)	Higher (long-term savings from reduced fuel use)	Higher (long-term savings from reduced fuel use)	High (long-term savings from reduced fuel use)
<b>Economics</b>	Depending on gas price, it is generally cost-effective	High initial cost, but cost savings over time	High initial cost, but cost savings over time	Better economics (savings from reduced fuel)	Better economics (savings from reduced fuel)	Good economics (savings from reduced fuel)
<b>Maintenance Requirements</b>	Low to Medium	Medium (requires cleaning and occasional repairs)	Medium (requires routine maintenance)	Medium (requires maintenance of two systems)	Medium (requires maintenance of two systems)	Medium (requires maintenance of two systems)
<b>Space Constraints</b>	Minimal (only space for TEG and gas pipelines)	High (requires a large area for panels)	High (requires large area and height for turbines)	Medium (space for TEG and PV, more efficient use)	Medium (space for TEG and Wind, more efficient use)	Medium (space for PV and Wind, more efficient use)
<b>Material Cost</b>	Medium	High (cost of panels and inverters)	High (cost of turbines)	High (combined cost of TEG and PV components)	High (combined cost of TEG and Wind components)	High (combined cost of PV and Wind components)
<b>Equipment Height</b>	Low (compact modules)	Medium (panels)	High (turbines)	Medium (height of combined TEG and PV)	Medium to High (height of combined TEG and Wind)	Medium-High (combined PV Wind)

Additionally, this system contributes substantially to renewable energy goals, as photovoltaic (PV) and TEG technologies work together to reduce dependence on fossil fuels and lower the carbon footprint. The hybrid system's lower carbon emissions highlight its environmental friendliness and long-term sustainability.

In summary, the comparative results show that the hybrid PV and TEG systems are superior in maximizing sustainability and operational efficiency on offshore platforms. This evaluation underscores the potential of hybrid systems to address future energy challenges.

**Table 6.** Scoring and Evaluation of TEG, Solar PV, Wind Energy, and Hybrid Systems

Parameter	TEG with Natural Gas	Solar PV	Wind Energy	Hybrid TEG + PV	Hybrid TEG +Wind	PV + Wind
Energy Source	4	4	4	5	5	5
Carbon Emissions	3	5	5	4	4	5
Operational Reliability	3	3	3	5	5	2
Energy Output Consistency	5	2	2	4	4	4
Scalability	3	5	5	5	5	5
Infrastructure Required	4	3	3	4	4	4
Installation Cost	3	2	2	3	3	3
Long-term Cost Efficiency	3	5	5	4	4	5
Economics	3	3	3	4	4	4
Maintenance Requirements	2	3	3	3	3	3
Space Constraints	5	2	2	3	3	3
Material Cost	4	2	2	3	3	3
Equipment Height	5	4	1	3	2	2
<b>Total</b>	<b>47</b>	<b>43</b>	<b>40</b>	<b>50</b>	<b>49</b>	<b>48</b>



**Figure 6.** Design concept hybrid system (PV+TEG).

The high scores and the detailed results, illustrated in Figure 6 and supported by the data in Table 6, affirm the system's effectiveness and efficiency. The design concept of the TEG and PV Hybrid system, with its optimal performance metrics, provides a robust solution for achieving sustainable energy outcomes.

The hybrid system depicted in Figure 6, which integrates PV and TEG with a 40% PV and 60% TEG distribution, offers an innovative solution for offshore platform operations by optimizing energy production and reducing environmental impact. In this configuration, 40% of the energy is derived from PV panels that convert sunlight directly into electricity, leveraging renewable

energy potential and diminishing dependence on fossil fuels. Simultaneously, 60% of the energy is generated by TEG, utilizing natural gas to produce electricity through the thermoelectric effect. This proportion ensures a continuous energy supply while significantly cutting CO2 emissions compared to systems that rely entirely on fossil fuels. Additionally, the system will be monitored via radio from an offshore to an onshore control room. However, some unexpected findings and discrepancies with existing research must be noted. For instance, while the hybrid system reduces natural gas consumption and CO2 emissions, it requires a larger area than the 100% TEG system.

**Table 7.** Technical data of the current energy system and the new energy system.

System	Area (m <sup>2</sup> )	Weight (kg)	Number of Devices		Natural Gas Consumption (GJ/year)	Emissions (ton CO <sub>2</sub> eq./year)
			PV	TEG		
100% TEG	5.6	2155	0	10	1165.41	1414.94
Hybrid	20.83	1500	9	6	699.25	848.96

This larger footprint could be a limitation in space-constrained offshore environments, despite the system's lighter weight, which simplifies structural requirements. Conflicting results may arise from variations in operational conditions and the efficiency of PV panels and TEG systems, which can differ based on specific offshore site characteristics.

The advantages of the hybrid system over the 100% TEG system are illustrated in Table 7, and the details are shown in Figure 6. The reliance on the 100% TEG system on greater amounts of natural gas results in higher CO<sub>2</sub> emissions, whereas the hybrid system demonstrates reduced natural gas consumption and lower emissions. Although the hybrid system requires a larger area, which could be seen as a drawback, its overall benefits, including improved energy continuity and reduced environmental impact, highlight its effectiveness. These findings suggest that while presenting a more sustainable solution, the hybrid system may encounter practical challenges related to spatial constraints and operational efficiency that differ from other research outcomes. As such, despite the promising results of the hybrid approach, further research may be necessary to address these discrepancies and optimize the system for specific offshore conditions.

Existing research provides comprehensive insights into integrating renewable energy sources in offshore oil and gas operations. This study identifies three key areas to enhance system performance and sustainability. These areas focus on operational improvements, technological innovations to maximize energy efficiency, and minimizing CO<sub>2</sub> emissions [27, 29]. First, optimizing energy use through hybrid system integration [8]. The core of this design lies in a hybrid system combining TEG with PV panels. By strategically integrating these systems, energy consumption can be optimized using renewable energy sources, as shown in Table 5. This integration ensures a reliable energy supply, reduces dependence on natural gas, and enhances overall energy efficiency, as demonstrated in Table 7. Second, evaluating hybrid system efficiency in offshore conditions. Solar energy potential varies significantly in offshore environments. Solar radiation may be limited due to weather conditions. Therefore, the energy generation performance of this system must be supported by more stable energy sources. Table 7 highlights the ability of the TEG and PV

combination to ensure system resilience in offshore environments, improving energy generation reliability while reducing the need for complex infrastructure. Third, developing integrated monitoring and control systems [20, 35]. Figure 6 shows that a robust monitoring and control system is essential to fully harness the hybrid system's potential. Overall, the proposed hybrid solar energy system and Thermoelectric for offshore oil and gas operations offers significant improvements in energy efficiency, reduced gas consumption, and lower CO<sub>2</sub> emissions, making it a superior alternative for sustainable energy generation in offshore environments.

The hybrid TEG system with renewable energy sources like PV can be used not only on offshore oil and gas platforms but also in other systems using TEG technology. This system is key in improving energy sustainability and reducing carbon emissions, which are critical for environmental sustainability. The research emphasizes the need for sustainable energy solutions that reduce reliance on fossil fuels while maintaining the operational reliability of offshore platforms.

However, the study has some limitations. The hybrid system's performance is affected by variable offshore weather, and its larger footprint could be challenging in space-limited areas. Additionally, practical issues such as integrating existing infrastructure and managing long-term operational costs require further study. The findings are important as they show the potential of hybrid systems to improve energy efficiency and sustainability, offering a strong alternative to fossil fuel-based systems. This research uniquely integrates PV and TEG technologies in offshore settings, addressing energy needs and environmental impacts. However, the study uses simulations and assumptions that may not fully represent real-world conditions. The integration of PV and TEG is still at the conceptual stage and needs further field testing. Future research should focus on resolving these challenges, advancing the technology, and optimizing spatial use. It's also important to improve how these systems connect with smart grid technology to boost energy efficiency and security [35]. Referring to international environmental policies makes this study more relevant. Global agreements like the Paris Agreement push for a shift to low-carbon technologies, including offshore energy systems. The IMO's 2030 Strategy also aims to reduce greenhouse gas emissions

by 40% by 2030 [44]. This research supports these goals by integrating renewable technologies like PV and TEG, which help reduce emissions and improve energy efficiency. Linking the study to these policies highlights the urgency of adopting sustainable energy systems to meet global climate goals.

#### 4. Conclusions

The concept design shows that a hybrid PV and TEG system effectively enhances energy efficiency and reduces carbon emissions in offshore oil and gas operations. By combining PV panels to harness solar energy with TEG systems utilizing natural gas, this hybrid solution lowers dependence on fossil fuels and improves the stability of the energy supply. This design represents a step toward more sustainable offshore operations. However, a significant finding is that the hybrid system requires a larger area than a 100% TEG system, which may present challenges in spatially constrained environments despite its environmental benefits. This study highlights a novel approach that merges PV and TEG technologies specifically for offshore platforms, showcasing its unique advantages in boosting sustainability. Discrepancies with existing research include the hybrid system's larger spatial footprint, which contrasts with anticipated emissions and fuel consumption reductions, potentially due to differing operational conditions and technological efficiencies. Future research should prioritize optimizing the hybrid system's performance and addressing spatial and operational challenges. Integrating smart grid technology could also enhance efficiency and reliability in offshore settings. Real-world testing and continued development are essential to fully realize this hybrid system's potential.

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