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Design of a 3.75 kW Hybrid Photovoltaic–Thermoelectric Generator Power Generation System for an Unmanned Offshore Gas Platform

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Abstract: A reliable power supply system is a fundamental requirement for unmanned offshore gas platforms because instrumentation, control, communication, and safety systems must operate continuously. Most studies on Photovoltaic–Thermoelectric Generator (PV–TEG) systems have focused on component optimization or laboratory-scale applications, whereas studies addressing system-level design for industrial applications remain limited. This study aims to design a 3.75 kW PV–TEG hybrid power generation system as a 24 VDC power supply for an unmanned offshore gas platform. An engineering design approach was adopted by determining the capacities of the photovoltaic modules, thermoelectric generator (TEG), battery bank, maximum power point tracking (MPPT), and DC–DC converter based on the load demand. The performance of the photovoltaic subsystem was evaluated using PVsyst, while the system power adequacy was evaluated through power balance analysis. The proposed design consists of 32 photovoltaic modules with a total installed capacity of 11.84 kWp, eight MPPT units, and an integrated PV–TEG configuration operating on a 24 VDC distribution system. Simulation results for the photovoltaic subsystem indicate an annual energy production of 16,220 kWh, a Performance Ratio of 77.19%, and a solar fraction of 98.70%. This study presents a system-level PV–TEG hybrid design that can serve as a basis for the development of highly reliable power supply systems for unmanned offshore gas platforms.

Keywords: Photovoltaic, Thermoelectric Generator, Hybrid Power Generation System, PVsyst, Offshore Gas Platform, 24 VDC.

INTRODUCTION

Unmanned offshore gas platforms require a reliable power supply system to ensure the continuous operation of instrumentation, communication, process control, and safety systems (Da Lio & Lazzaretto, 2022). The remote location of these facilities, combined with limited access for inspection and maintenance, means that failures in the power supply system may disrupt operational continuity and gas production (Wang et al., 2025). Therefore, the power generation system must provide high reliability (Al-Sefri & Al-Shaalan, 2019), require minimal maintenance, and ensure a continuous power supply.

In the offshore oil and gas industry, electrical power demand is commonly supplied by internal combustion engine-based power generation systems (Li et al., 2024). Although these systems are capable of delivering high power output, they contain moving components that require periodic maintenance, thereby increasing operation and maintenance costs, particularly for unmanned facilities. As an alternative, renewable energy technologies have been increasingly adopted to improve the reliability of power supply systems. Photovoltaic (PV) systems (Zaidi, 2018) convert solar radiation into electrical energy, whereas thermoelectric generators (TEGs) (Y G et al., 2022) directly convert thermal energy into electricity through the Seebeck effect without the use of moving components. The operating characteristics of these two technologies are complementary because PV systems generate electricity only when solar radiation is available, whereas TEGs can continuously generate electricity as long as a heat source is available.

Research on hybrid PV–TEG systems has progressively shifted from fundamental studies toward performance enhancement. Various PV–TEG integration configurations have been reviewed, demonstrating that system configuration, integration methods, and thermal parameters are the primary factors influencing the energy output of hybrid systems (U. A & Jumaat, 2022). More recent studies have shown that efficiency improvement is mainly achieved through the optimization of system configuration, heat sinks, phase change materials, and other cooling techniques to reduce PV module temperature while increasing the temperature difference across the TEG (Zamanipour et al., 2024). A similar approach has been reported through the development of PV–TEG systems employing passive thermal management based on heat pipes, radiative cooling, and heat sinks to improve system energy production (Montero et al., 2025).

Beyond configuration optimization and thermal management, recent studies have also focused on waste heat utilization and overall system performance enhancement. Hybrid PV–TEG systems that utilize heat generated by PV modules and integrate various maximum power point tracking (MPPT) methods have been shown to improve voltage, efficiency, and power output compared with standalone PV systems (Qasim et al., 2023). Furthermore, the development of PV–TEG prototypes for energy harvesting has demonstrated that integrating a TEG with a PV module can improve system efficiency by utilizing thermal energy that would otherwise be dissipated (Sahari et al., 2022).

Recent developments have also emphasized control strategies and power electronics. A comprehensive review of MPPT algorithms for hybrid PV–TEG systems has been reported (Yang et al., 2023), while an optimization method based on generalized particle swarm optimization (GEPSO) has been proposed to improve maximum power point tracking under varying operating conditions (Ejaz, 2022). Meanwhile, the integration of TEGs with nanofluid-based cooling systems has been investigated to enhance the thermal management of PV modules (Selimefendigil et al., 2023), whereas the application of micro-channel heat pipes and conventional heat pipes has been evaluated to improve the efficiency of hybrid PV–TEG systems (Zamanipour et al., 2024).

Although these studies have contributed to efficiency improvement, thermal management optimization, MPPT algorithm development (Yang et al., 2023), and PV–TEG system configuration (Saleh et al., 2021), most of them remain focused on component performance enhancement, control strategies, or laboratory-scale validation. Comprehensive studies addressing the system-level design of hybrid PV–TEG power generation systems for industrial applications remain limited. For unmanned offshore gas platforms, the primary challenge is not merely improving the efficiency of individual components but designing a system capable of determining the appropriate capacities of photovoltaic modules, thermoelectric generators, battery banks, maximum power point tracking (MPPT) units, DC–

DC converters, and a 24 VDC power distribution system (ANSI/ISA–50.00.01, 2002; IEC 61131-2, 2017) according to the required electrical load demand. In addition, the capability of the system to provide a continuous power supply must be verified through power balance analysis. These aspects have rarely been addressed in an integrated manner, resulting in a gap between research focused on PV–TEG technology performance enhancement and the practical requirements for industrial system implementation (Babu & Ponnambalam, 2018).

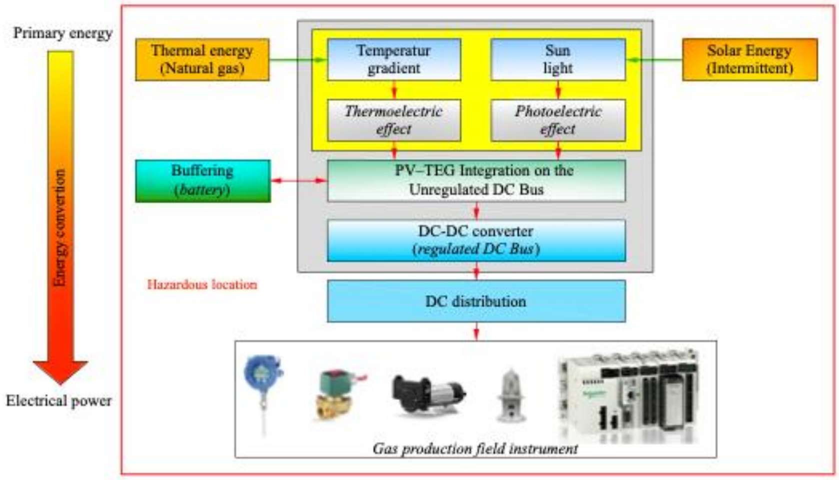
Based on this research gap, the present study aims to design a 3.75 kW hybrid PV–TEG power generation system to provide a 24 VDC (ANSI/ISA–50.00.01, 2002; IEC 61131-2, 2017) continuous power supply for an unmanned offshore gas platform using an engineering design approach. The proposed system was developed by determining the capacities of the major system components according to the electrical load demand, evaluating the performance of the photovoltaic subsystem using PVsyst software (Baqir & Channi, 2022; Mermoud André & Villoz Michel, 2026) based on the meteorological conditions of the study site, and verifying the system's capability to satisfy the required power demand through power balance analysis.

This study contributes to the development of a system-level engineering design framework for a 3.75 kW hybrid PV–TEG power generation system intended for unmanned offshore gas platform applications. Unlike previous studies that primarily focused on component performance optimization, the proposed approach integrates the sizing of major system components, the configuration of a 24 VDC power distribution system (ANSI/ISA–50.00.01, 2002; IEC 61131-2, 2017), photovoltaic subsystem performance evaluation using PVsyst, and verification through power balance analysis within a unified engineering design framework for industrial implementation.

METHODS

This study adopted an engineering design approach to develop a hybrid Photovoltaic–Thermoelectric Generator (PV–TEG) power generation system (Babu & Ponnambalam, 2018) as a continuous DC power supply for an unmanned offshore gas platform. The proposed system was designed by utilizing solar radiation and heat generated from natural gas combustion as energy sources (Shaukat et al., 2023) to supply electrical power for instrumentation, process control, communication, and safety systems through a 24 VDC (ANSI/ISA–50.00.01, 2002; IEC 61131-2, 2017) power distribution system.

The proposed system concept is illustrated in Figure 1 (Aljibory et al., 2021; Shaukat et al., 2023). The photovoltaic system converts solar radiation into electrical energy through the photovoltaic effect (Al-Ali et al., 2025), whereas the thermoelectric generator (TEG) converts thermal energy directly into electrical energy through the Seebeck effect (Adam et al., 2013; Y G et al., 2022). The output of the photovoltaic system is delivered through a *maximum power* point tracking (MPPT) unit, whereas the output of the thermoelectric generator is connected directly to the unregulated DC bus. The battery bank is also connected to the unregulated DC *bus* and functions as an energy buffer to maintain power supply continuity. Subsequently, the electrical energy available at the unregulated DC bus is converted by a DC–DC converter into a regulated DC bus with a nominal voltage of 24 VDC (ANSI/ISA–50.00.01, 2002; IEC 61131-2, 2017) before being distributed to all electrical loads.

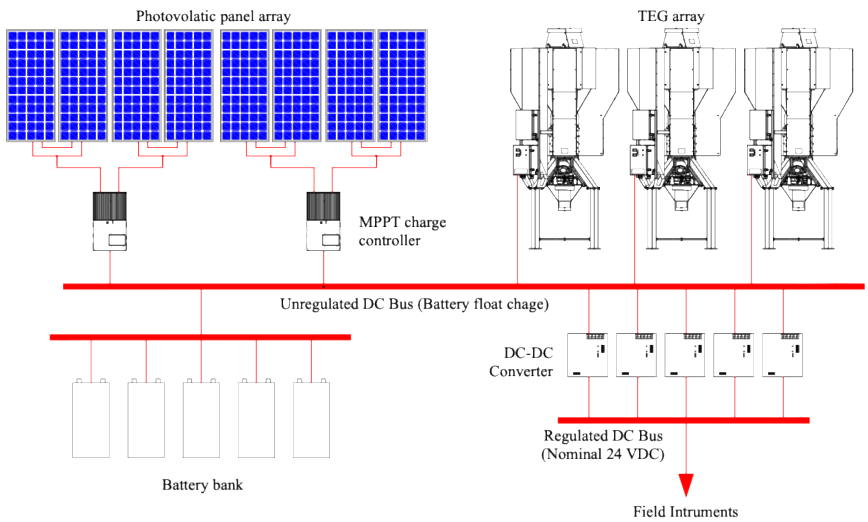


Source: Research results.

Figure 1. Concept of the hybrid PV–TEG power generation system for an unmanned offshore gas platform.

The system design process began with the identification of the platform electrical load requirements based on the operational load profile. Based on these requirements, the capacities of the photovoltaic modules (Pharos Marine, n.d.), thermoelectric generators (Global Power Technologies, n.d.-b), battery bank (Linden & Reddy, 2002), maximum power point tracking (MPPT) unit (Kar & Patra, 2021), and DC–DC converter (Sekar et al., 2026) were determined to ensure a continuous electrical power supply. Each subsystem was designed according to the characteristics of its energy source and the electrical load demand, resulting in a system configuration capable of meeting the operational requirements of the unmanned offshore gas platform.

The resulting system configuration is presented in Figure 2. The photovoltaic system is connected to the unregulated DC bus through the MPPT unit to maximize the power output of the photovoltaic modules, whereas the thermoelectric generator is connected directly to the unregulated DC bus as a continuous power generation source. The battery bank is connected to the same bus and functions as an energy buffer (Čović et al., 2024; Pop et al., 2008) to maintain power supply continuity whenever an imbalance occurs between the generated power and the load demand. Subsequently, the DC–DC converter converts the voltage on the unregulated DC *bus* into a regulated DC bus with a nominal voltage of 24 VDC before supplying power to all electrical loads.



Source: Research results.

Figure 2. Proposed configuration of the hybrid PV–TEG system.

The performance of the photovoltaic subsystem was evaluated using PVsyst software (Mermoud André & Villoz Michel, 2026) based on the meteorological data of the study site to estimate the annual energy production and system performance parameters. The evaluation results were subsequently integrated with the design results of the other subsystems in a power balance analysis to verify that the proposed system was capable of continuously supplying the required electrical power of 3.75 kW for the unmanned offshore gas platform.

Hybrid System Design Basis

The hybrid PV–TEG (Shaukat et al., 2023) system was initially sized using a balanced 50:50 power allocation between the two generation subsystems. This allocation was adopted as a common design basis for determining the required capacities of the PV and TEG subsystems and did not imply equal instantaneous power generation, as the two energy sources have different operating characteristics and availability. Accordingly, the required power contribution of each subsystem was defined as

$$P_{PV,req} = P_{TEG,req} = \frac{P_{design}}{2} \quad (1)$$

where P_{design} is the total design power requirement of 3.75 kW.

Thermoelectric Generator Sizing

The TEG subsystem was sized using the GPT Model 1500 (Global Power Technologies, n.d.-b), which has a rated electrical output of $P_{TEG}, rated = 530\ W$ at the reference ambient temperature $T_{ref} = 20°\text{C}$. To account for the offshore design ambient temperature of $T_{amb} = 35°\text{C}$, the rated output was corrected using the manufacturer-specified temperature derating coefficient $k_T = 1.40\ W/°\text{C}$ (Global Power Technologies, n.d.-a), as expressed by

$$P_{TEG,design} = P_{TEG,rated} - k_{T(T_{amb} - T_{ref})} \quad (2)$$

The minimum number of TEG units required to satisfy the allocated TEG power requirement was then determined as

$$N_{TEG} = \left\lceil \frac{P_{TEG,req}}{P_{TEG,design}} \right\rceil \quad (3)$$

where the calculated number of units was rounded upward to ensure that the installed TEG capacity was not lower than the allocated power requirement. The resulting TEG configuration was subsequently included in the hybrid power-balance calculation.

Photovoltaic System Sizing

The PV subsystem was sized based on the allocated PV power requirement and the solar irradiation at the offshore study location obtained from the Global Solar Atlas (GSA) (Global Solar Atlas, 2026). The required PV energy (Duffie & Beckman, 2013) over the selected operating period was determined as

$$E_{PV,req} = P_{PV,req} t \quad (4)$$

where t is the annual operating period used to determine the required PV energy (Duffie & Beckman, 2013). Considering the available solar irradiation and the design performance ratio (Duffie & Beckman, 2013), the required installed PV capacity was calculated as

$$P_{PV,installed} = \frac{E_{PV,req} \mathrm{G_{STC}}}{H_{solar} PR} \quad (5)$$

where $G_{STC} = 1\ kW/m^2$ is the reference solar irradiance under standard test conditions (STC) (Huang et al., 2026), H_{solar} is the solar irradiation at the study location, and PR is the design performance ratio. The required number of PV modules was subsequently determined as

$$N_{PV} = \left\lceil \frac{P_{PV,installed}}{P_{module}} \right\rceil \quad (6)$$

where P_{module} is the rated power of an individual PV module. The resulting PV configuration was subsequently evaluated using PVsyst (Mermoud André & Villoz Michel, 2026) under the specified site conditions.

Hybrid Power Balance

The hybrid power balance was formulated based on the combined power contributions of the PV and TEG subsystems. The total hybrid generation power was expressed as

$$P_{hybrid} = P_{PV} + P_{TEG} \quad (7)$$

where P_{PV} and P_{TEG} represent the power contributions of the PV and TEG subsystems, respectively. The power adequacy criterion was defined as

$$P_{hybrid} \geq P_{design} \quad (8)$$

where P_{design} represents the total design power requirement of the hybrid system.

RESULTS AND DISCUSSION

Results

The hybrid Photovoltaic–Thermoelectric Generator (PV–TEG) power generation system (Babu & Ponnambalam, 2018) was designed to provide a continuous electrical power supply of 3.75 kW through a 24 VDC power distribution system for an unmanned offshore gas platform. Based on the 50:50 design allocation, the PV and TEG subsystems were each assigned a design power contribution of 1.875 kW. The PV subsystem supplied its allocated contribution during periods of sufficient solar availability, whereas the TEG subsystem continuously supplied its allocated contribution by utilizing thermal energy generated from natural gas combustion.

At the offshore design ambient temperature of 35°C, the corrected electrical output of the GPT Model 1500 was 509 W per unit. Accordingly, four TEG units were required to satisfy the allocated TEG power contribution, resulting in a total design capacity of 2.036 kW. The TEG subsystem design results are summarized in Table 1.

Table 1. TEG subsystem design results

Parameter	Design Result
TEG model	GPT Model 1500
Allocated TEG power contribution	1.875 kW
Rated electrical output	530 W/unit
Reference ambient temperature	20°C
Design ambient temperature	35°C
Temperature derating coefficient	1.40 W/°C
Corrected electrical output	509 W/unit
Required number of TEG units	4 units
Total TEG design capacity	2.036 kW

Source: Authors' calculations (2026).

The performance of the photovoltaic subsystem was subsequently evaluated using PVsyst software. The design and simulation results are presented in Table 2.

Table 2. Comparison between the design results and the PVsyst simulation results of the photovoltaic subsystem

Parameter	Design Results	PVsyst Results	Δ
Number of PV modules	32 units	32 units	–
Module configuration	16 strings × 2 modules	16 strings × 2 modules	–
Installed capacity	11.84 kWp	11.84 kWp	–
Number of MPPT units	8 units	8 units	–

Parameter	Design Results	PVsyst Results	Δ
PV array area	62.3 m²	62.3 m²	–
Annual energy production	16,586 kWh/year	16,220 kWh/year	−366 kWh/year
Performance Ratio (PR)	83.0%	77.19%	−5.81 pp
Battery bank capacity	12,500 Ah	8,815 Ah	−3,685 Ah

Source: Authors' calculations and PVsyst simulation results (2026).

The design and simulation results produced an identical photovoltaic subsystem configuration consisting of 32 PV modules arranged in 16 strings × 2 modules, with an installed capacity of 11.84 kWp, a PV array area of 62.3 m², and eight MPPT units. Differences were observed in the annual energy production, Performance Ratio (PR) (Peng et al., 2024), and battery bank capacity (Linden & Reddy, 2002), as presented in Table 2. The simulation estimated an annual energy production of 16,220 kWh/year, a Performance Ratio (PR) of 77.19%, and a battery bank capacity of 8,815 Ah.

Furthermore, the PVsyst simulation indicated a total available solar energy of 17,477 kWh/year and a usable electrical energy production of 16,220 kWh/year. The simulation also reported a solar fraction of 98.70%.

Hybrid Power Balance

Based on the design results, the PV subsystem was assigned a design power contribution of 1.875 kW, while the four TEG units provided a total design capacity of 2.036 kW. Therefore, the total hybrid generation power was

$$P_{hybrid} = 1.875 + 2.036 = 3.911\ kW$$

The resulting hybrid generation power exceeded the total design power requirement of 3.75 kW by 0.161 kW, corresponding to a power margin of 4.29%. The power adequacy criterion was therefore satisfied, as expressed by

$$P_{hybrid} = 3.911\ kW \geq P_{design} = 3.750\ kW$$

This result confirms that the combined PV–TEG generation capacity met the specified design power requirement under the defined design conditions.

Discussion

The identical configuration obtained from the design and simulation results indicates that the PVsyst model (Mermoud André & Villoz Michel, 2026) accurately represents the proposed system design. Because the system configuration remained unchanged, the differences observed between the design and simulation results were not caused by modifications to the design parameters but rather by the analytical approach employed during the simulation process. Consequently, the simulation results provide a more realistic evaluation of the proposed system under operating conditions that more closely resemble actual field conditions.

The simulated annual energy production was 366 kWh/year lower than the design estimate. This difference indicates that the simulation accounts for various operational losses that are not fully incorporated into the design calculations, including the effects of module temperature, module mismatch (Wurster & Schubert, 2014), cable losses (Ekici & Kopru, 2017), converter efficiency, and energy storage system losses. By incorporating these factors, the simulation provides a more realistic estimate of annual energy production and therefore offers a more representative basis for evaluating system performance.

A similar difference was observed in the Performance Ratio (PR) (Peng et al., 2024), which was 5.81 percentage points lower than the design value. The reduction in PR indicates that a portion of the solar energy received by the photovoltaic modules cannot be converted into electrical energy because of losses occurring throughout the system. Nevertheless, the simulated PR value of 77.19% (Fonseca et al., 2025; Peng et al., 2024) indicates that the photovoltaic subsystem retained a substantial proportion of its reference energy yield after accounting for system losses.

The difference in battery bank capacity between the design and the PVsyst model does not represent a modification of the proposed system design. The design capacity of 12,500 Ah was determined based on the required energy demand, autonomy period, and design criteria, whereas PVsyst (Baqir & Channi, 2022; Mermoud André & Villoz Michel, 2026) employs battery models available in its internal database for simulation purposes. Therefore, the battery capacity used in the simulation was not considered a performance evaluation parameter but rather a component of the photovoltaic system simulation model.

The simulation yielded a solar fraction of 98.70%, indicating that approximately 98.70% of the annual energy demand could be supplied by the photovoltaic subsystem. However, a high solar fraction alone does not guarantee continuous power availability because the output of the photovoltaic subsystem depends on the availability of solar radiation. During nighttime or periods of reduced solar irradiance, photovoltaic energy production decreases, making an additional energy source capable of providing continuous power necessary.

In the proposed system, continuous power supply is provided by the thermoelectric generator (TEG) subsystem, which utilizes thermal energy generated from natural gas combustion. Unlike the photovoltaic subsystem, whose output depends on environmental conditions, the TEG can continuously generate electrical energy as long as a heat source is available. The integration of these two subsystems therefore creates a complementary hybrid power generation system in which the photovoltaic subsystem serves as the primary energy source during periods of solar irradiance, while the TEG maintains continuous power supply when photovoltaic energy production decreases or is unavailable.

The power balance analysis further verified the adequacy of the proposed hybrid generation capacity. The allocated PV power contribution of 1.875 kW and the TEG design capacity of 2.036 kW resulted in a total hybrid generation power of 3.911 kW. This value exceeded the design power requirement of 3.75 kW by 0.161 kW, corresponding to a power margin of 4.29%. Therefore, the combined PV–TEG generation capacity satisfied the specified power adequacy criterion under the defined design conditions.

Overall, the design and simulation results demonstrate that the proposed hybrid PV–TEG system configuration is capable of meeting the required 3.75 kW electrical load through a 24 VDC power distribution system for an unmanned offshore gas platform. The close agreement between the design and simulation results indicates that the proposed system can be accurately represented using PVsyst, while the complementary integration of the photovoltaic and thermoelectric generator subsystems ensures a continuous power supply for instrumentation, communication, process control, and safety systems. The principal novelty of this study lies in the development of a system-level engineering design framework that integrates component sizing, 24 VDC power distribution configuration, photovoltaic subsystem evaluation using PVsyst, and verification through power balance analysis within a single design methodology. Unlike previous studies that primarily emphasized component-level performance optimization or laboratory-scale validation, the proposed approach provides an integrated engineering basis for implementing hybrid PV–TEG power generation systems in unmanned offshore industrial facilities requiring reliable continuous power.

CONCLUSIONS AND RECOMMENDATIONS

Conclusion

This study successfully designed a 3.75 kW hybrid Photovoltaic–Thermoelectric Generator (PV–TEG) power generation system to provide a 24 VDC power supply for an unmanned offshore gas platform. The system was designed by integrating a photovoltaic subsystem, thermoelectric generators, a battery bank, maximum power point tracking (MPPT) units, and DC–DC converters based on the required electrical load demand and power balance analysis. The power balance analysis showed that the combined PV–TEG generation capacity reached 3.911 kW, exceeding the 3.75 kW design power requirement by 4.29%. The PVsyst evaluation showed that the photovoltaic subsystem configuration was consistent with the proposed system design, while integration with the TEG enabled continuous power supply when solar energy was unavailable. Therefore, the proposed design has the potential to serve as an alternative sustainable power supply system for unmanned offshore gas platform applications requiring high operational reliability and minimal maintenance.

Limitations

This study was limited to the system design stage and the evaluation of the photovoltaic subsystem using PVsyst simulations (Baqir & Channi, 2022; Mermoud André & Villoz Michel, 2026). The analysis did not include prototype implementation or field testing; therefore, the effects of actual operating conditions, component degradation, long-term system reliability, and economic aspects could not be comprehensively evaluated. Consequently, the findings of this study should be considered as a design basis that requires further validation through implementation under actual operating conditions.

Recommendations

Future research is recommended to implement a prototype of the proposed hybrid PV–TEG system under representative operating conditions to validate the design and simulation results. Further studies may also include long-term system reliability assessment, *life cycle cost* (LCC) analysis, and optimization of the capacities of photovoltaic modules, thermoelectric generators, and battery banks according to load characteristics and environmental conditions. In addition, future work may investigate the performance of the proposed system under different operating locations and meteorological conditions to develop a design that is more adaptable for unmanned offshore gas platform applications.

Author Contributions

All authors made substantial contributions to the conception of the study, methodology development, analysis and interpretation of the results, manuscript preparation and revision, and approved the final version of the manuscript for publication.

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