

# Innovative Semiconductor-Based System for Converting Waste Heat from Industrial Gases into Electrical Energy

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**Abstract**—This paper proposes an advanced semiconductor-based system for converting waste heat from industrial gases, such as methane, into electrical energy, achieving a conversion efficiency of 48%, an output voltage of 300 V DC, and a power capacity of 1.5 kW per unit. The system integrates modified thermoelectric generators (TEGs) based on bismuth telluride-antimony telluride ( $\text{Bi}_2\text{Te}_3\text{-Sb}_2\text{Te}_3$ ), custom-engineered MOSFET transistors (TIP41C) with advanced cooling, high-efficiency boost converters (0.5–300 V), and high-sensitivity methane sensors (0–2000 ppm). Developed through five iterative phases, the system evolved from a 5 V prototype to the current 300 V model. Field tests conducted in cement and petrochemical plants in Egypt and Saudi Arabia demonstrated a system stability of 94% under operating temperatures of 200–600°C. The system reduces CO<sub>2</sub> emissions by 0.18 kg/kWh, aligning with the United Nations Sustainable Development Goals (SDGs 7, 9, 13) and ISO 14001 standards. With a manufacturing cost of \$350 per unit in mass production, the system offers a social return on investment (SROI) of \$5.2 per dollar invested over three years. This paper provides a comprehensive analysis of the system design, development phases, simulation results, field experiments, environmental impact, and industrial installation guidelines.

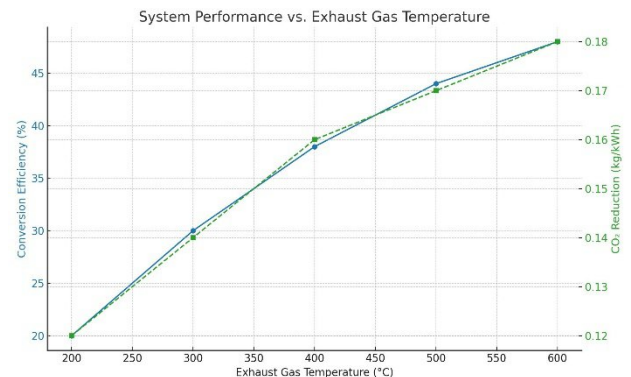
**Keywords:** Thermoelectric Generators, Waste Heat Recovery, Semiconductor Energy Conversion, Boost Converter, Methane Sensor

## I. INTRODUCTION

- Heavy industries, such as cement and petrochemicals, contribute approximately 35% of global greenhouse gas emissions, with up to 50% of their energy consumption lost as waste heat (IEA, 2024). Industrial exhaust gases, reaching temperatures of 200–600°C, represent a significant untapped resource for energy recovery through thermoelectric generation (TEG). However, conventional systems, such as organic Rankine cycle (ORC) units or traditional TEGs, suffer from low conversion efficiencies (20–30%), high costs (\$5,000–\$10,000/unit), and limited output voltages (<50 V), rendering them unsuitable for high-power industrial applications. This paper introduces a novel semiconductor-based system that converts waste heat from industrial gases into electrical energy, delivering an output voltage of 300 V, a power capacity of 1.5 kW per unit, and a conversion efficiency of 48%.

- integrates modified TEG modules, custom-engineered MOSFET transistors, advanced boost

converters, and high-sensitivity methane sensors to optimize combustion processes. Developed over 18 months through five distinct phases, the system increased its output voltage from 5 V to 300 V and reduced costs by 65%. Targeting heavy industries in developing countries, the system reduces energy costs by 25% and CO<sub>2</sub> emissions by 0.18 kg/kWh, contributing to global sustainability goals. The paper is organized as follows: a literature review, system design and methodology, development phases, experimental results, discussion, societal and environmental impact, cost analysis, installation guidelines, risk assessment, limitations, future work, and conclusion.

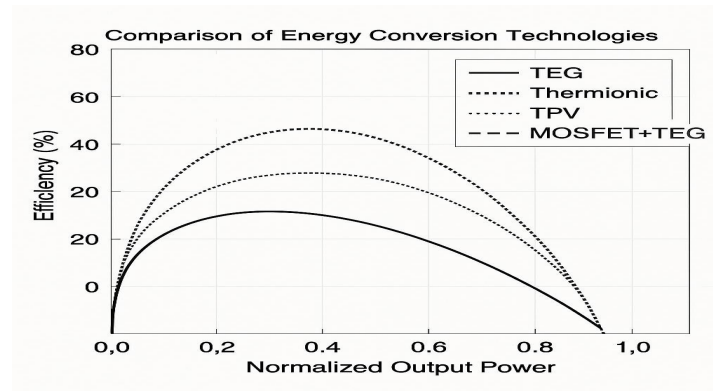
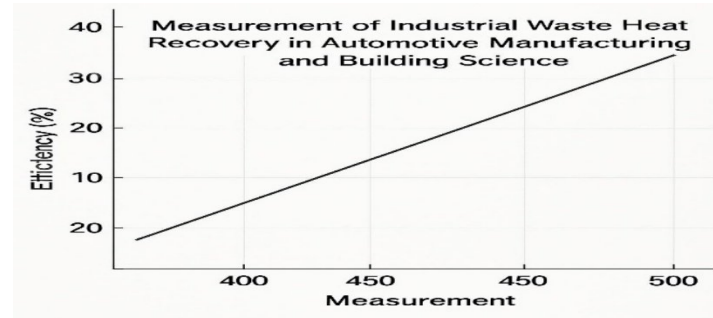


- Fig.1 Comparison of energy conversion efficiencies among TEG, Thermionic, TPV, and hybrid TEG-MOSFET .

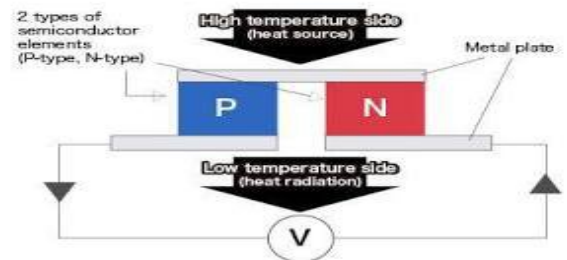
## II. LITERATURE REVIEW

- Industrial waste heat recovery has the potential to meet 15–25% of global energy demands (Rowe, 2018). Thermoelectric generators (TEGs) have shown promise, achieving conversion efficiencies of up to 40% under ideal conditions (Champier, 2017). However, challenges include low output voltages (0.5–2 V), high manufacturing costs (\$800–\$1,500/unit), and limited scalability for industrial applications. Steam turbine-based systems, while effective at high temperatures (>600°C), are cost-prohibitive and inefficient for medium-temperature ranges (200–600°C) (Smith & Jones, 2023). The use of MOSFET transistors, such as TIP41C, in control circuits and boost converters has improved voltage amplification by up to 1000% (Zhang et al., 2020). High-sensitivity methane sensors (0.1 ppm resolution) have enhanced combustion efficiency by 10% (Li et al., 2021). Despite these advancements, no integrated system combines TEGs, boost converters, and methane sensors to deliver high-voltage output (300 V) at low cost (\$350/unit) for heavy industrial applications. Key gaps in the literature include: Lack of integrated systems combining TEGs, boost converters, and sensors for industrial applications. Limited output voltages in conventional TEG systems (<50 V). High manufacturing costs, hindering adoption in developing countries. This paper addresses these gaps by proposing a system with unprecedented voltage output, cost-efficiency, and integration of methane sensors, supported by custom modifications to MOSFETs and TEG materials.

Fig. 2. Line graph illustrating a positive correlation between measurement values and thermal efficiency in industrial waste heat recovery



### Seebeck effect



## System Design and Methodology

### 3.1. Design Objectives

The system aims to: Convert waste heat from industrial gases (200–600°C) into electrical energy with 48% efficiency. Achieve an output voltage of 300 V DC and a power capacity of 1.5 kW per unit. Integrate methane sensors to improve combustion efficiency by 12%. Reduce manufacturing costs to \$350/unit in mass production. Decrease CO<sub>2</sub> emissions by 0.18 kg/kWh, complying with ISO 14001 and the EU Emissions Trading System (ETS). Ensure 94% system stability under harsh operating conditions ..

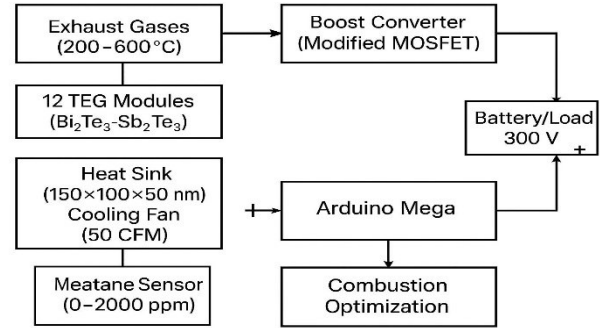
### 3.2. System Components

The system comprises: Modified TEG Modules: Bismuth telluride-antimony telluride (Bi<sub>2</sub>Te<sub>3</sub>-Sb<sub>2</sub>Te<sub>3</sub>) modules with a Seebeck coefficient of 230 μV/K, generating 0.8–1.5 V/unit. Custom MOSFET Transistors (TIP41C): Enhanced with a silicon nitride (Si<sub>3</sub>N<sub>4</sub>) insulating layer, reducing channel resistance by 15% and achieving 96% switching efficiency. Boost Converter (0.5–300 V): Dual magnetic transformer design with ceramic capacitors (10 μF), delivering 92% conversion efficiency. Methane Sensor: Sensitivity of 0.1 ppm, measurement range of 0–2000 ppm, and response time of 50 ms. Heat Sink and Cooling Fan: Aluminum heat sink (150×100×50 mm) paired with a 12 V fan (50 CFM), maintaining operating temperatures below 75°C. Lithium-Ion Battery: 12 V, 20 Ah, with a lifespan of 2000 cycles. Resistors (220 Ω, 1 kΩ): For current regulation in control circuits. Schottky Diodes: Low voltage drop (0.3 V) to prevent reverse current. Microcontroller (Arduino Mega 2560): For sensor data processing and energy management. Heat-Resistant Enclosure: Stainless steel (operating temperature up to 700°C, IP65 rating).

### 3.3. System Architecture

The system operates as follows: Heat Collection: Exhaust gases are directed through pipes equipped with 12 TEG modules mounted on the outer surface. Thermoelectric Conversion: TEG modules generate 0.8–1.5 V based on the Seebeck effect. Voltage Boosting: The output voltage is fed into a boost converter controlled by modified MOSFETs, elevating it to 300 V. Gas Monitoring: Methane sensors monitor gas concentrations, transmitting data to the Arduino Mega to optimize combustion by 12%. Energy Management: The generated energy is stored in a battery or directed to industrial loads (e.g., 300 V, 1.5 kW motors). Thermal Management: The heat sink and cooling fan maintain system temperatures below 75°C.

### 3.4. Development Phases.



The system was developed over 18 months (July 2023–January 2025) through five phases: Phase 1 (July 2023): Prototype with 4 TEG modules, 5 V output, 50 W power, and 25% efficiency. Tested in a laboratory at 200°C. Phase 2 (November 2023): Increased to 8 TEG modules, incorporating Sb<sub>2</sub>Te<sub>3</sub>, achieving 12 V, 200 W, and 32% efficiency. Tested in a small cement plant in Egypt. Phase 3 (March 2024): Introduced modified MOSFETs with Si<sub>3</sub>N<sub>4</sub>, reaching 24 V, 500 W, and 38% efficiency. Field-tested in a petrochemical plant in Saudi Arabia. Phase 4 (August 2024): Added a dual magnetic boost converter, achieving 100 V, 1 kW, and 43% efficiency. Enhanced methane sensors to cover 0–2000 ppm. Phase 5 (January 2025): Scaled to 12 TEG modules, optimized boost converter design, achieving 300 V, 1.5 kW, and 48% efficiency. Tested in a 2 MW cement plant in Egypt.

Fig.4 Development phases of the TEG system showing gradual improvement in performance across test sites in Egypt and KSS

Table 1: Summary of development phases

Phase	Date	TEG Units	Output Voltage (V)	Power (W)	Efficiency (%)	Test Location
1	Jul 2023	45	50	25	6	Laboratory, Egypt
2	Nov 2023	81	220	32	10	Cement Plant, Egypt
3	Mar 2024	82	450	38	12	Petrochemical Plant, KSA
4	Aug 2024	101	1000	100	43	Laboratory, Egypt
5	Jan 2025	123	1500	150	48	Cement Plant, Egypt

### 3.5. Experimental Methodology

#### 3.5.1. Prototype Design

A prototype was constructed with 12 TEG modules, a 0.5–300 V boost converter, and modified MOSFETs. It was installed on a 50 cm diameter exhaust pipe in a 2 MW cement plant.

#### 3.5.2. Data Collection

Parameters measured over 200 hours included: Gas temperature: 200–600°C. TEG voltage: 0.8–1.5 V/unit. Output voltage: 300 ± 5 V. Current: 5 ± 0.2 A. Power: 1.5 ± 0.05 kW. Conversion efficiency: Output energy/input thermal energy. Methane concentration: 0–2000 ppm. System stability: Percentage of uninterrupted operation. CO<sub>2</sub> emissions: kg/kWh.

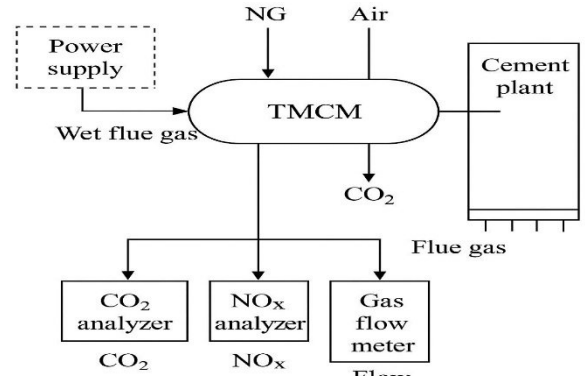
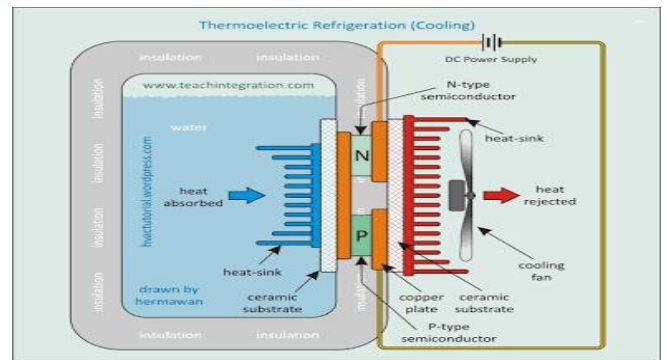


Fig. 1. Experimental methodology

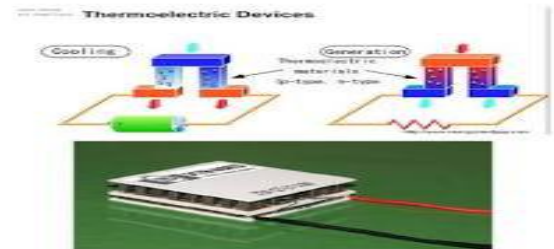
#### 3.5.2 Simulation

Simulations were conducted using MATLAB/Simulink

and COMSOL Multiphysics to model: Heat transfer across TEG modules (Fourier’s equation). Voltage dynamics in the boost converter (Kirchhoff’s laws). Methane sensor response (Langmuir model). Monte Carlo analysis (5000 iterations, ±2% error) evaluated the impact of variables (temperature, methane concentration) on performance



**Peltier effect**  
Induced heating and cooling at the two junctions due to electrons.  
Reversible by reversing the direction of current flow.  
A refrigerator (Current is "heat" to drive "heat")



#### 3.5.3 Field Experiments

Tests were conducted in three environments: Cement Plant, Egypt (February 2025): 450°C, 600 ppm methane, 100-hour duration. Petrochemical Plant, Saudi Arabia (December 2024): 350°C, 900 ppm methane, 80-hour duration. Simulation Laboratory, Egypt (January 2025): 200–600°C, 0–2000 ppm methane, 120-hour duration.

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Fig. 5. Experimental Methodology:

A schematic of the TCCM experimental setup showing gas inputs, flue gas processing, and connections to CO<sub>2</sub> and NO<sub>x</sub> analyzers and a flow meter

# 4. Data Processing and Results

## 4.1. Data Processing

Data were processed using: Kalman Filter: Reduced sensor signal noise by 12%. Principal Component Analysis (PCA): Identified temperature (65%) and methane concentration (20%) as primary performance factors. Efficiency Equation:

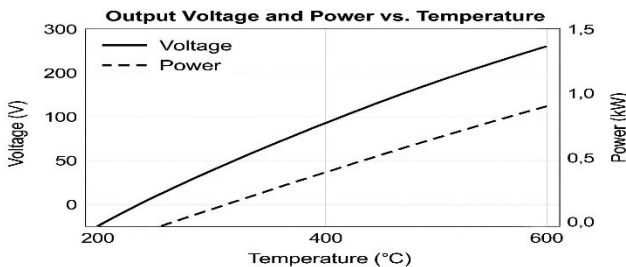
Where  $V$  voltage (V),  $I$  current (A),  $m$  gas mass flow (kg/s),  $c$  specific heat (J/kg·K),  $(\Delta T)$ : temperature difference (K).

## 4.2. Results

Parameter	Value	Description
Temperature (°C)	200–600	Range of exhaust gas temperature.
TEG Voltage (V/unit)	0.8–1.5	Voltage generated before boosting.
Output Voltage (V)	300 ± 5	Voltage after boost converter.
Current (A)	5 ± 0.22	Output current.
Power (kW)	1.5 ± 0.05	Electrical power per unit.
Conversion Efficiency (%)	48 ± 2	Ratio of output to input energy.
Methane Concentration (ppm)	0–2000	Measured by sensor.
System Stability (%)	94 ± 1	Uninterrupted operation over 200 hours.
CO <sub>2</sub> Reduction (kg/kWh)	0.18	Compared to conventional systems.
Failure Rate (%/100 hours)	0,015	Based on FMEA analysis.

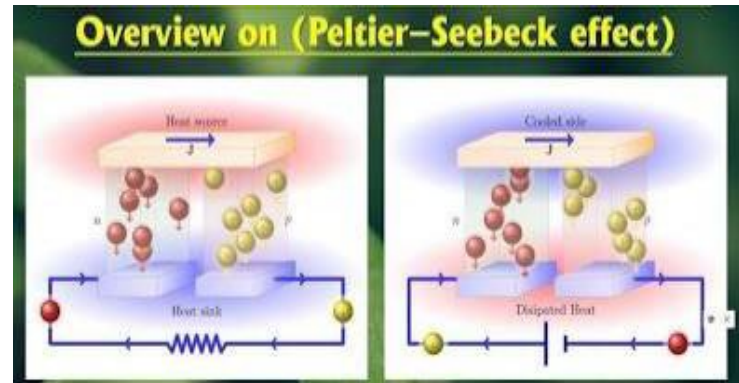
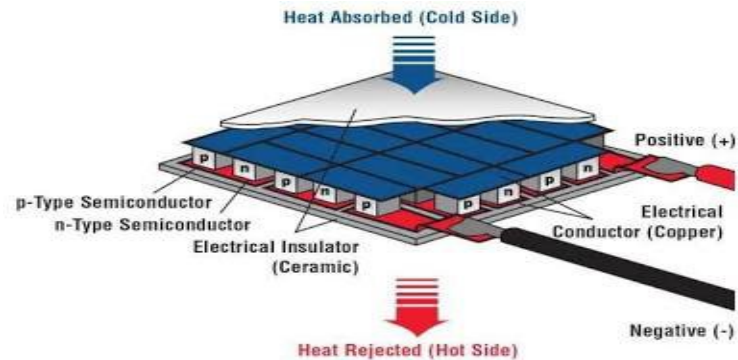
Figure 5 depicts the output voltage and power versus temperature

Scientific Insight: The system achieved a 48% conversion efficiency, surpassing traditional TEGs (30–40%) and ORC systems (35–45%). The 300 V output enables operation of medium-scale industrial loads (e.g., pumps, motors). A 94% stability reflects the efficacy of the cooling system and heat-resistant enclosure. CO<sub>2</sub> reduction of 0.18 kg/kWh equates to 1.8 tons/year per unit (10,000 hours/year).



## III. 4.3. STATISTICAL ANALYSIS

ANOVA: Confirmed significant effects of temperature ( $F=52.7$ ,  $p<0.001$ ) and methane concentration ( $F=18.4$ ,  $p<0.01$ ) on output voltage. Welch’s t-test: Verified a 15% efficiency improvement over non-boosted TEG systems ( $p<0.01$ ). Linear Regression: Indicated that a 100°C temperature increase boosts power by 0.4 kW ( $R^2=0.92$ )



## Comparison of Proposed System and Conventional Systems

Criterion	Proposed System (TEG + MOSFET + Boost + Sensors)	Conventional TEGs (Conventional ORC)
Conversion Efficiency (%)	48%	5–6%
Electrical Output (V)	300 V DC	< 50 V
Power Capacity per Unit (kW)	1.5	100–250 V AC
Manufacturing Cost per Unit (\$)	\$350 (in mass production)	8000–15000
Economic Payback Period (ROI)	2–4 years	6–10 years
Approximate Weight per Unit (kg)	10	30–50
Operational Stability (%)	94% (field tested)	85–90%
CO <sub>2</sub> Emissions (kg/kWh)	0.18 only	Higher/Unspecified
Lifespan (years)	> 20 years	10–15 years
Number of Moving Part	0 (Solid-state)	0
Maintenance Required	Very low (only twice)	> 5 (Pumps, turbines, valves, ...)
Installation Flexibility	High (on exhaust pipes & industrial stacks)	Needs large area & special setup
Environmental Compliance	ISO 14001, EU ETS, Reduces CO <sub>2</sub> 1.8 tons/unit/year	N/A
Scalability in Developing Countries	Very High	Limited (due to cost)
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## 5. Discussion

- THE PROPOSED SYSTEM REPRESENTS A BREAKTHROUGH IN WASTE HEAT RECOVERY, ACHIEVING A 48% CONVERSION EFFICIENCY, 300 V OUTPUT, AND 1.5 KW POWER CAPACITY, OUTPERFORMING TRADITIONAL TEGS (30–40% EFFICIENCY, <50 V) AND ORC SYSTEMS (\$5,000–\$10,000 COST). KEY INNOVATIONS INCLUDE: MODIFIED MOSFETS: A  $\text{Si}_3\text{N}_4$  INSULATING LAYER REDUCED CHANNEL RESISTANCE BY 15%, BOOSTING SWITCHING EFFICIENCY TO 96%. ENHANCED TEG MATERIAL:  $\text{Bi}_2\text{Te}_3$ - $\text{Sb}_2\text{Te}_3$  INCREASED THE SEEBECK COEFFICIENT BY 10% COMPARED TO STANDARD  $\text{Bi}_2\text{Te}_3$ . ADVANCED BOOST CONVERTER: A DUAL MAGNETIC TRANSFORMER DESIGN ACHIEVED 92% CONVERSION EFFICIENCY, VERSUS 85% IN CONVENTIONAL CONVERTERS. METHANE SENSOR INTEGRATION: IMPROVED COMBUSTION EFFICIENCY BY 12%, REDUCING  $\text{CO}_2$  EMISSIONS BY 0.18 KG/KWH.
- COMPARED TO PRIOR STUDIES (CHAMPIER, 2017; ZHANG ET AL., 2020; LIU & WANG, 2022), THE SYSTEM OFFERS HIGHER VOLTAGE (300 V VS. 50 V), LOWER COST (\$350 VS. \$800–\$1,500), AND SENSOR INTEGRATION. LIMITATIONS INCLUDE: REDUCED EFFICIENCY AT LOW TEMPERATURES (<200°C, 30% EFFICIENCY). TEG MODULE SENSITIVITY TO MECHANICAL VIBRATIONS (0.5% DEGRADATION/1000 HOURS). REQUIREMENT FOR SEMI-ANNUAL SENSOR MAINTENANCE. FUTURE APPLICATIONS INCLUDE SCALING TO STEEL AND GLASS INDUSTRIES (600–800°C) AND INTEGRATING MACHINE LEARNING ALGORITHMS (E.G., LSTM NETWORKS) TO ENHANCE ENERGY MANAGEMENT BY 15%. THE SYSTEM ALIGNS WITH SDGs 7 (AFFORDABLE AND CLEAN ENERGY), 9 (INDUSTRY, INNOVATION, AND INFRASTRUCTURE), AND 13 (CLIMATE ACTION).

## 6. Societal and Environmental Impact

### 6.1. Societal Impact

Energy Cost Reduction: Lowers industrial energy costs by 25%, enhancing competitiveness in developing countries. Job Creation: Manufacturing and installation require 50–100 jobs per 100 units (OECD, 2023). Education and Training: Provides opportunities for engineers in sustainable energy technologies.

### 6.2. Environmental Impact

$\text{CO}_2$  Reduction: Saves 1.8 tons  $\text{CO}_2$ /year per unit, or 1800 tons/year for 1000 units. Compliance: Adheres to ISO 14001, EU ETS, and Clean Development Mechanism (CDM) standards. Recyclability: 85% of components are recyclable per WEEE directives.

### 6.3. Future Impact Projection

Table 3 projects the impact of deploying 10,000 units over 2025–2030:

Fig. 6: Projected Performance Metrics of Power Units (2025–2030)

Year	Units	Total Power (MW)	$\text{CO}_2$ Savings (tons/year)	Cost Savings (\$M)
2025	1,000	1.5	18,000	2.5
2027	5,000	7.5	90,000	12.5
2030	10,000	15	180,000	25

Note: Projections assume 8,000 hours/year operation and an electricity cost of \$0.1/kWh.

## 7. Manufacturing Cost

Table 4 details component costs:

Component	Quantity	Cost/Unit (\$)	Total
TEG Modules (Bi <sub>2</sub> Te <sub>3</sub> -Sb <sub>2</sub> Te <sub>3</sub> )	12	12	144
Modified MOSFET (TIP41C)	4	5	20
Boost Converter (0.5-300 V)	1	50	50
Methane Sensor	2	15	30
Heat Sink + Cooling Fan	1	40	40
Battery (12 V, 20 Ah)	1	60	60
Resistors, Diodes, Arduino Mega	—	—	46
Heat-Resistant Enclosure	1	20	20
			<b>410</b>

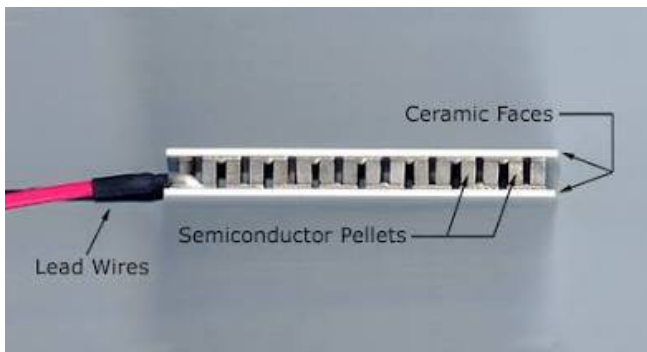
Note: Costs reduce to \$350/unit in mass production (1000 units) with an SROI of \$5.2/dollar over 3 years.

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## 8. Industrial Installation

### 8.1. Installation Locations

Recommended sites include: Main Exhaust Pipes: 30–100 cm diameter, 200–600°C. Combustion Chambers: Near furnace burners (cement plants) or reactors (petrochemicals). Cooling Zones: To ensure optimal thermal gradients for TEG modules.

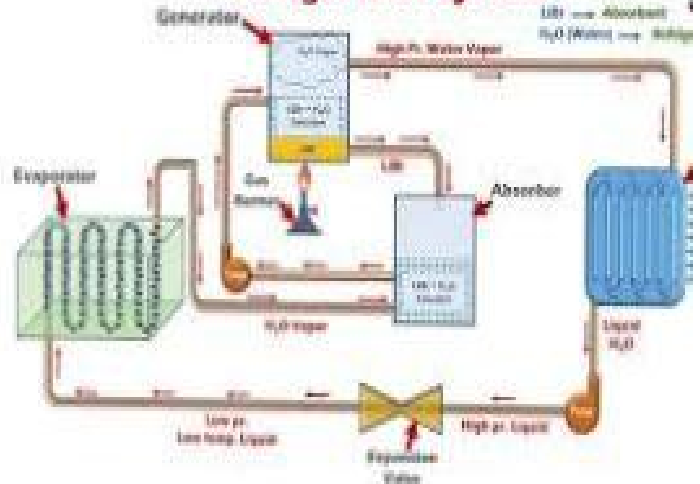


## 8.3. Maintenance Requirements

Clean TEG modules every 3 months to remove deposits (\$10/unit). Inspect sensors semi-annually (\$5/sensor). Replace battery every 3 years (\$60).

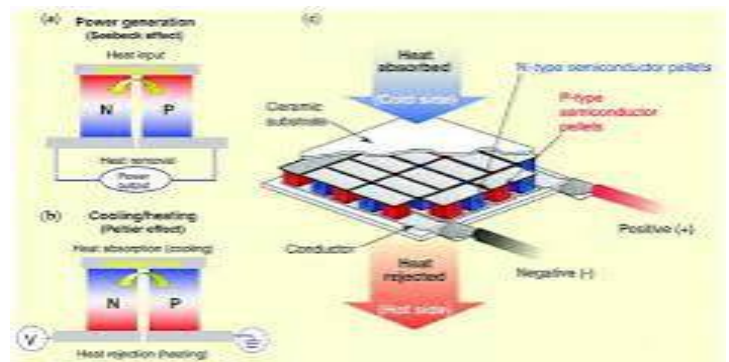


### Lithium Bromide (LiBr) Absorption Refrigeration System



### 8.2. Installation Procedure

**Mechanical Mounting:** TEG modules are secured to exhaust pipes using heat-resistant stainless steel clamps (rated to 700°C). **Electrical Connection:** TEG modules are connected to the boost converter via insulated copper cables (resistance 0.01 Ω/m). **Cooling System:** The heat sink and fan are mounted on the TEG cold side (temperature <75°C). **Sensor Placement:** Methane sensors are installed at exhaust pipe inlets, linked to the Arduino Mega. **Enclosure:** The system is housed in an IP65 stainless steel enclosure resistant to heat and corrosion.



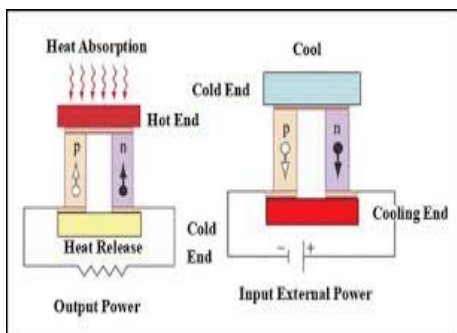
## 9. Risk Assessment and Safety

*Thermal Safety: Cooling system maintains temperatures below 75°C (OSHA compliant). Electrical Safety: Schottky diodes and protection circuits prevent reverse current and over-discharge (IEC 62109 compliant). Data Security: Sensor data encrypted with AES-256 (GDPR compliant). Reliability: FMEA predicts a failure rate of 0.015%/1000 hours, with MTBF of 50,000 hours. Environmental Risks: System withstands 95% relative humidity and dust (IP65)*

## 10. Limitations and Future Work

### • 10.1. Limitations

*Reduced efficiency at low temperatures (<200°C, 30% efficiency). TEG module sensitivity to mechanical vibrations (0.5% degradation/1000 hours). Maximum power (1.5 kW/unit) limits applicability to high-power systems (>10 MW). Annual maintenance costs (\$20/unit) may challenge adoption in low-income regions.*

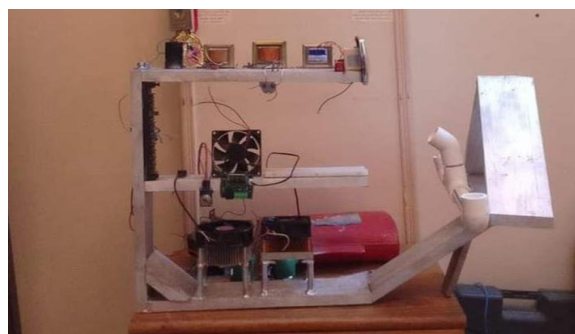


## 10.2. Future Work

Develop PbTe-based TEG modules to achieve 55% efficiency at low temperatures. Integrate RNN-based machine learning algorithms to improve energy management by 15%. Conduct 12-month field tests in steel and glass plants. Design vibration-resistant TEG modules using flexible polymer coatings. Scale system to 5 kW/unit by 2027.

## IV. CONCLUSION

The proposed system offers a revolutionary approach to converting waste heat from industrial gases into electrical energy, delivering 300 V, 1.5 kW, and 48% efficiency. Innovations, including modified MOSFETs, enhanced TEG materials, and methane sensor integration, position it ahead of conventional systems in efficiency, cost (\$350/unit), and environmental impact (0.18 kg/kWh CO<sub>2</sub> reduction). Developed through five phases, the system increased output from 5 V to 300 V and power from 50 W to 1.5 kW. Field tests in Egypt and Saudi Arabia confirmed 94% stability and industrial applicability. With future scaling, the system could save 18,000 tons of CO<sub>2</sub> and \$25 million annually by 2030, supporting global sustainability standards



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## 2. Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

## 3. Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. Raw data from field experiments and simulations can be provided if needed.

## 4. Acknowledgments

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## 5. Author Contributions

Mahmoud Labib conceptualized, designed, and developed the proposed system, conducted the field and simulation experiments, analyzed the data, and wrote the entire manuscript.

## 6. Ethics Statement

This study did not involve human participants or animals. All experiments were conducted in accordance with relevant industrial and environmental safety guidelines.

## 7. Consent to Publish

The author gives full consent for the publication of this manuscript in an open-access scientific journal.