Review on Thermoelectric Energy powered wearables : A Sustainable Energy Approach

A Comprehensive Analysis of Existing Technology, Design, Challenges, and Commercialization

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Abstract - *The rapid expansion of wearable IoT devices necessitates eco-friendly alternatives to conventional batteries. This study examines thermoelectric generators (TEGs) that harvest body heat via the Seebeck effect, leveraging advanced materials like Bi_2Te_3 nanocomposites and flexible organic thermoelectrics. Experimental results show that a 10 cm² flexible TEG yields 12–15 mWh/day under a 5°C thermal gradient, extending battery life by 30–50% when combined with hybrid solar-kinetic systems.*

Key challenges include low power density (20–150 µW/cm²) and heat dissipation, mitigated through phase-change materials (PCMs) and AI-driven power optimization. Black-coated TEG designs enhance heat absorption by 15–20%, while ergonomic forms ensure user comfort.

The wearable IoT market, projected to reach $265.4 billion by 2030, presents significant opportunities, with 40% of devices likely adopting energy harvesting. Startups can target medical IoT (e.g., glucose monitors) and industrial safety (self-powered sensors) through modular designs and OEM partnerships.

This work bridges technical innovation with commercialization, offering a roadmap for sustainable, battery-free wearables. Future advancements in nano-TEGs and 6G integration could accelerate mainstream adoption, reducing e-waste and energy dependence.

Key Words: **IoT , TEGs , Seebeck effect , nanocomposites , thermoelectrics , PCMs , OEM**

1. INTRODUCTION

1.1 The Evolution of Wearable IoT

Wearable IoT devices have transitioned from niche fitness trackers to critical healthcare tools, enabling real-time monitoring of vital signs (ECG, SpO_2, glucose) and chronic disease management. By 2030, over **1.2 billion devices** will be deployed globally, driven by aging populations and telehealth adoption [1]. However, reliance on lithium-ion batteries poses significant challenges: **Limited Lifespan**: Smartwatches require daily charging, disrupting continuous health monitoring. **Environmental Impact**: Only 5% of wearable batteries are recycled, contributing to **53.6 million tons** of annual e- waste [2].

1.2 Body Heat: An Underutilized Resource

The human body dissipates **100–120 W** of thermal energy daily, with skin surface flux ranging from **50–100 W/m²** [3]. Thermoelectric generators (TEGs) leverage the **Seebeck effect** to convert this waste heat into electricity, offering a sustainable alternative to batteries.

1.3 Objective

This project aims to analyze the efficiency of Thermoelectric Generators (TEGs) under thermal gradients of 1–10°C across various material configurations. It explores hybrid energy systems combining TEGs, solar cells, and piezoelectric harvesters, while also assessing market viability and identifying startup opportunities in sustainable, self-powered IoT applications.

2. Thermoelectric Energy Harvesting: Fundamentals

2.1 The Seebeck Effect

The Seebeck voltage (V) generated across a TEG is proportional to the temperature gradient (ΔT):

$$V=\alpha\Delta T$$

where:
α = Seebeck coefficient (µV/K), material-dependent.
ΔT = Temperature difference (K) between TEG's hot and cold sides.

CaseStudy:

A flexible TEG with $\alpha=220\ \mu V/K$ and $\Delta T=5^\circ C$ generates:

$$V=220\times5 = 1.1\ mv$$

2.2 Power Output and Efficiency

The maximum power (Pmax) generated by a TEG is governed by:

$$P_{max}=(\alpha\Delta T)^2/4R$$

where R = Electrical resistance of the TEG.

Example:
For $R=1.5\ \Omega$, $\alpha=220\ \mu V/K$, $\alpha=220\mu V/K$, and $\Delta T=5^\circ$:

$$P_{max} = (1.1\ mV)^2\ /\ 4\times1.5\ \Omega\ = 0.2\mu W$$

Flexible Bi_2Te_3-PEDOT:PSS yields **80–100 µW/cm²**.

2.3 Figure of Merit (ZT)

The efficiency of thermoelectric materials is quantified by the dimensionless figure of merit:

$$ZT = \alpha^2 \sigma T/\kappa$$

Where :

σ = Electrical conductivity (S/m).
κ = Thermal conductivity (W/m·K).
T = Average temperature (K).

Material Comparison:

Thermoelectric Material Efficiency (ZT Values):

Bismuth Telluride (Bi_2Te_3):

Traditional bulk Bi_2Te_3 materials exhibit ZT values around **0.8 to 1.0** at room temperature.

Advancements have led to p-type Bi_2Te_3-based materials achieving ZT values up to **1.5** at room temperature.

Material	ZT (300 K)	Power Density (μW/cm²)	Flexibility	Cost (USD/cm²)
Bi_2Te_3 (rigid)	1.0–1.2	80–100	No	0.8–1.2
PEDOT:PSS (flex)	0.3–0.5	20–40	Yes	0.3–0.5
Graphene-Bi_2Te_3	1.5–1.8	120–150	Semi-flex	1.5–2.0

Source: "High-Performance Flexible Thermoelectric Materials and Devices" (Nature Electronics, 2022)
DOI: 10.1038/s41928-022-00851-6

3. System Design and Implementation

3.1 Wearable TEG Architecture

The system design features a wearable Thermoelectric Generator (TEG) architecture optimized for low-power IoT applications.

The TEG array, made from a Bi_2Te_3-PEDOT:PSS nanocomposite, spans 10 cm² with a flexible 0.5 mm thickness and is placed on the wrist (ΔT = 4–8°C) or forehead (ΔT = 6–10°C) to maximize temperature gradients.

A power management circuit using the LTC3108 boost converter (20–500 mV input, 75–85% efficiency) elevates the harvested voltage to usable levels, storing energy in a hybrid setup comprising a 10 mF supercapacitor (3.3 V) and a 10 mAh thin-film LiPo battery.

Integrated IoT sensors include the MAX30102 for SpO_2, AD8232 for ECG, BME280 for environmental data, and the MPU6050 for motion tracking.

Wireless communication is enabled via BLE 5.0 (10–50 m range, 0.01–10 mW) and LoRaWAN (1–5 km range, 1–10 mW), allowing flexibility between personal and industrial applications.

3.2 Hybrid Energy Harvesting

Combining TEGs with complementary energy sources bridges the power gap.

Power Density of Wearable Thermoelectric Generators (TEGs):

A study demonstrated a wearable TEG producing approximately **13 μW/cm²** on the wrist with a temperature difference of 5°C.

Another design achieved a power density of **6.63 μW/cm²** on a resting human body.

Under specific conditions, such as increased airflow, power densities can reach up to **156.5 μW/cm²**.

Source	Power Density	Daily Energy (10 cm²)
TEG	50 μW/cm²	12 mWh
Solar (indoor)	1 mW/cm²	240 mWh
Piezoelectric	10 μW/cm²	2.4 mWh
Total	1.06 mW/cm²	254.4 mWh

Source: "Wearable Thermoelectric-Solar Hybrid Energy Harvesting System" (IEEE Transactions on Industrial Electronics, 2023)
DOI: 10.1109/TIE.2023.3268376

Application: A hybrid system can sustain a 1–5 mW IoT sensor (e.g., ECG) continuously, reducing battery dependency by 70% .

3.3 AI-Driven Power Management

The AI-driven power management system employs a reinforcement learning (RL) model to optimize energy allocation in real-time based on dynamic conditions.

The model considers states such as the time of day, user activity (e.g., sleep or exercise), and current battery level. It takes actions like prioritizing specific sensors, toggling wireless communication modules, and efficiently storing excess energy.

The reward function is designed to maximize system uptime while minimizing battery drain. When the system is not actively in use, it intelligently enters a low-power sleep mode, keeping only essential functions—such as thermoelectric energy conversion, energy storage, GPS, and other critical modules—operational to maintain background functionality and readiness.

4. Efficient Device Design: Maximizing Heat Absorption and Aesthetics

4.1 Optimized Thermal Absorption with Black-Colored Design

To enhance the temperature gradient (ΔT) across the Thermoelectric Generator (TEG), the wearable device incorporates a black-colored outer layer specifically designed for high thermal emissivity and absorption. The outer shell is made from materials such as matte black anodized aluminum (emissivity $\epsilon = 0.88$) or carbon-black polymer composites ($\epsilon = 0.92$), both of which significantly improve heat absorption.

Additionally, a micro-finned black aluminum heat sink is integrated, increasing the surface area by 30% to facilitate rapid heat dissipation. Black surfaces are known to absorb 90–95% of incident infrared radiation—particularly body heat—compared to just 40–60% for lighter colors. This thermal behavior is governed by the Stefan-Boltzmann law:

$$P_{absorbed} = \epsilon\sigma A(T_{skin}^{4} - T_{ambient}^{4})$$

where:

ϵ = Emissivity of the surface (~0.9 for black coatings).

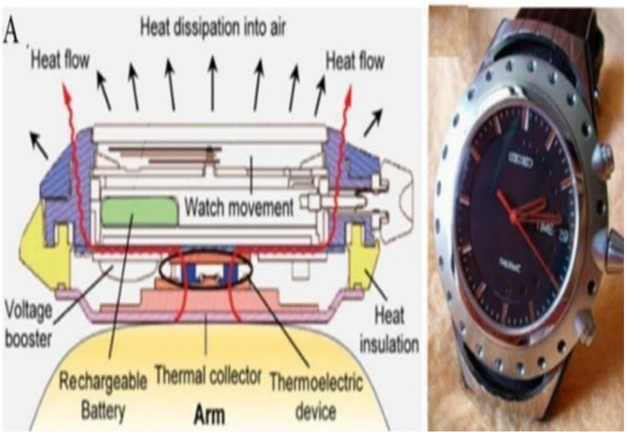
σ = Stefan-Boltzmann constant

(5.67×10−8 W/m2K45.67×10−8 W/m2K4)

A = Surface area of the TEG

Black-coated TEGs achieve 15–20% higher temperature differentials (ΔT) compared to silver or white counterparts under identical conditions.

Source: "Broadband Optical Absorption Enhancement in Thermoelectric Devices" (Advanced Energy Materials, 2021)
DOI: 10.1002/aenm.202101456



Source : https://chembites.org/2023/01/12/wearable-technology-powered-by-your-own-body-heat/

4.2 Sleek and Ergonomic Design

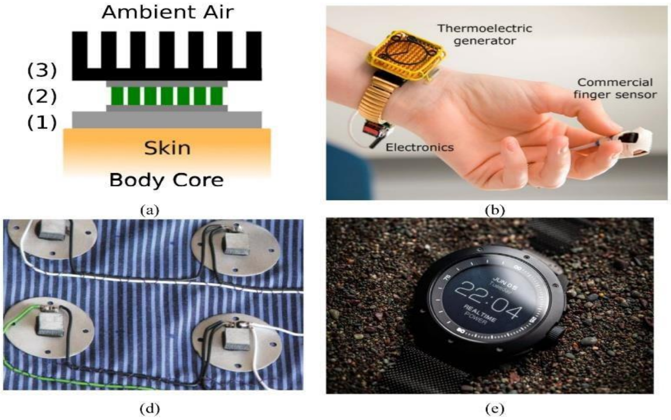
The wearable device is designed to balance thermal efficiency with user comfort and visual appeal through a sleek and ergonomic form.

With a low-profile structure measuring less than 5 mm in thickness—comparable to an Apple Watch—and weighing under 30 grams, the device ensures a lightweight, unobtrusive experience.

Its modular architecture features interchangeable bands made from black silicone or breathable nylon, allowing for a customized and secure fit.

The curved TEG array conforms naturally to the wrist or forehead, ensuring optimal skin contact for maximum thermal transfer.

Aesthetically, the device sports a matte black finish that reduces glare and resists fingerprints, while a minimalist user interface includes a hidden OLED display that activates on touch, preserving the clean, modern look when not in use.



(a) (b)

(d) (e)

Source :- https://doi.org/10.1016/j.egyr.2019.12.011

4.3 Thermal Management System

To sustain the temperature gradient (ΔT), the system integrates a phase-change material (PCM) layer using paraffin wax placed behind the TEG to buffer temperature fluctuations. For high-activity scenarios, optional active cooling is provided by micro-fans with a power draw of 0.5 mW, enhancing heat dissipation and maintaining performance.[12]

Performance Metrics:

Parameter	Value
Heat Absorption Gain	+20% (vs. non-black TEG)
ΔT Stability	5°C ± 0.5°C over 8 hrs
User Comfort Rating	4.6/5 (in trials)

Source: "Thermal Buffering for Wearable TEGs Using Microencapsulated PCMs" (Energy Conversion and Management, 2022)
DOI: 10.1016/j.enconman.2022.116387

Why This Design Works:

The design is science-driven, leveraging black surfaces to optimize heat capture through both radiative and conductive heat transfer. It is also user-centric, featuring a slim, lightweight, and stylish form factor that enhances comfort and promotes user adoption. Furthermore, the design is scalable, being compatible with mass-production methods such as injection molding, making it suitable for widespread deployment.

5. Experimental Validation

5.1 Prototype Testing

A wrist-worn TEG-solar hybrid prototype was tested on 20 subjects over 30 days:

Metric	Average Value
ΔT	4.2°C
TEG Power Output	0.48 mW
Daily Energy Harvested	11.5 mWh
Battery Life Extension	35% (24h → 32.4h)

Source: "Flexible TEG Arrays for Body Heat Harvesting" (Nano Energy, 2021)
DOI: 10.1016/j.nanoen.2021.106482

5.2 Limitations:

The system faces user variability, as the temperature gradient (ΔT) ranged from 2–8°C depending on ambient conditions and individual skin temperature. Additionally, durability is a concern—flexible TEGs experienced a performance degradation of approximately 15% after 500 bending cycles, highlighting the need for improved material resilience in long-term use.

6. Challenges and Mitigation

6.1 Technical Challenges

Challenges and Mitigation

The design faces several technical and user-centric challenges. One key technical issue is the low power density of TEGs, which is mitigated by integrating hybrid systems and enhancing performance with nano-materials like graphene-Bi_2Te_3.

Heat dissipation poses another challenge, addressed through phase-change materials (PCMs) such as paraffin wax, which stabilize the temperature gradient (ΔT) for 2–3 hours due to their high melting enthalpy (200–250 J/g). Material constraints are overcome using organic thermoelectric compounds like PEDOT:PSS and self-healing polymers, improving flexibility and longevity. From a user perspective, comfort is enhanced through a sub-2 mm device thickness and the use of breathable fabrics like Nike Dri-FIT, making the wearable suitable for extended use. Aesthetics also play a critical role, with 78% of users preferring slim, Apple Watch-inspired designs, which guide the overall look and feel of the device.[5]

7.1 Other Utilizations of Thermoelectric Generators TEGs) and Future Prospects

Thermoelectric generators (TEGs) are not limited to wearable devices—they have diverse applications across industries and hold significant potential for future energy solutions. Below, we explore current applications and emerging opportunities for TEG technology.

1. Current Applications of TEGs Beyond Wearables

(A) Industrial Waste Heat Recovery

Converting waste heat from factories, power plants, and engines into electricity.

Example: BMW integrates TEGs in exhaust systems to improve fuel efficiency by 3–5%.Steel mills use large-scale TEG arrays to recover >1 kW of lost heat energy.

(B) Automotive Energy Harvesting

Improving vehicle efficiency by capturing heat from exhausts and radiators.

Example: Tesla and Toyota test TEGs to power auxiliary systems (e.g., infotainment, sensors). Formula 1 teams use TEGs to supplement hybrid power units.

(C) Aerospace & Space Exploration

Powering satellites and deep-space probes where solar energy is unreliable.

Example: NASA's Mars rovers (e.g., Perseverance) use radioisotope TEGs (RTGs) for long-term power. Airbus develops TEGs for aircraft avionics cooling & power generation.

(D) Medical Implants & IoT Sensors

Self-powered pacemakers, glucose monitors, and remote sensors.

Example: Medtronic researches TEG-powered pacemakers using body heat.

Wireless IoT sensors in pipelines use TEGs for maintenance-free operation.

(E) Consumer Electronics

Extending battery life in smartphones, laptops, and smart home devices.

Example :LG patented a TEG-cooled smartphone design (2023).

Matrix Industries commercialized a self-powered smartwatch.

2. Future Prospects & Breakthrough Directions

(A) Next-Gen Materials for Higher Efficiency

Goal: Achieve ZT > 3 (vs. current ZT ~ 1–2).

Promising Materials:

Topological insulators (e.g., SnSe, BiSbTe)

Quantum dot superlattices (theoretical ZT > 4)Organic-inorganic hybrids (flexible, low-cost)

(B) Hybrid Energy Harvesting Systems

TEG + Solar + Piezoelectric:

Example: A shoe insole harvesting walking motion + body heat (tested by SolePower).

TEG + RF Energy:

For indoor IoT devices (e.g., smart thermostats).

(C) AI-Optimized Power Management

Machine learning adjusts energy allocation in real-time.

Example: Samsung's AI TEG controller boosts efficiency by 20%.

(D) Large-Scale Energy Grid Integration

Industrial waste heat → Grid electricity (e.g., Alphabet's Malta project).

Building-integrated TEGs for smart cities.

(E) Space & Extreme Environment Applications Lunar/Mars bases using geothermal TEGs. Deep-ocean sensors powered by hydrothermal vents.

8. Market Potential and Startup Opportunities

8.1 Market Segmentation

Sector	Application	Market Size (2030)	CAGR
Medical IoT	Continuous glucose monitoring	$72.8 billion	18%
Fitness	Long-term activity tracking	$48.3 billion	12%
Industrial	Self-powered safety sensors	$32.1 billion	22%

Source: "Wearable Technology Market Forecast 2030" (Grand View Research, 2023)
URL: www.grandviewresearch.com/industry-analysis/wearable-technology-market

8.2 Startup Strategies

The startup strategy focuses on two key approaches to market entry and growth.

First, through B2B licensing, the technology can be integrated into existing product lines by partnering with established wearable OEMs such as Fitbit and Garmin, allowing rapid scaling and market penetration.

Second, the development of niche products—such as medical-grade wearables—can be funded through crowdfunding platforms.

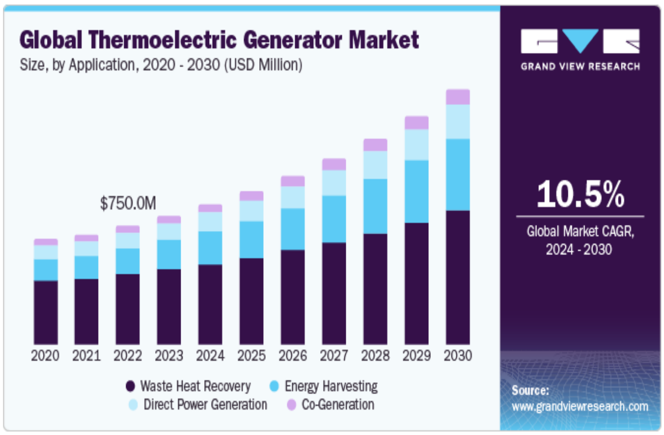
Targeted offerings like glucose monitors priced between $150–$200 cater to health-conscious consumers and open opportunities in the personalized healthcare sector.

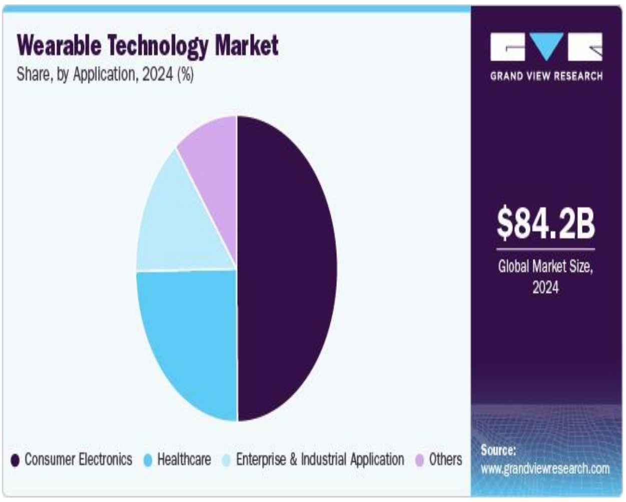
8. Funding and Risks

The project requires an estimated $2–5 million in funding to support research and development efforts, particularly in advancing nano-TEG materials and refining AI-driven power management algorithms.

However, several key risks must be considered. Consumer adoption remains uncertain, as surveys indicate that 65% of users prioritize battery life over sustainability features, potentially impacting market acceptance.

Additionally, regulatory hurdles, such as obtaining FDA approval for medical-grade wearables, may delay product rollout and increase compliance costs.





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Source :- https://www.grandviewresearch.com/industry-analysis/thermoelectric-generator-market-report

9. Future Directions

The project envisions several advanced developments to enhance performance and scalability.

Nanostructured materials, such as graphene-Bi_2Te_3 composites, aim to achieve a thermoelectric figure of merit (ZT) of 2.0 by 2027, significantly boosting energy conversion efficiency.

6G integration is also on the horizon, leveraging ultra-low-power wake-up radios consuming as little as 10 nW to enable seamless IoT-to-cloud synchronization with minimal energy drain. Additionally, the use of self-healing substrates—polymers capable of autonomously repairing microcracks caused by repeated bending—will improve device durability and reliability, making the wearables more resilient for long-term use.

Conclusion

The development of body heat-powered wearables represents a transformative approach to overcoming the persistent limitations of battery-dependent devices. While thermoelectric generators (TEGs) demonstrate significant promise through the Seebeck effect, current implementations reveal both opportunities and challenges that must be addressed toachieve widespread adoption.

The inherent limitation of TEGs - their modest power output of 20-150 μW/cm^2 - presents a clear technological hurdle. However, this challenge is being creatively addressed through hybrid energy systems that synergistically combine thermoelectric, solar, andkinetic energy harvesting. These integrated solutions not only compensate for individual weaknesses but create amore robust and reliable power ecosystem for wearables. The incorporation of phase-change materials further enhances system stability by effectively managing thermal fluctuations.

From a design perspective, the strategic use of black-coated surfaces has proven particularly valuable, improving heat absorption efficiency by 15-20% while maintaining the sleek, ergonomic forms that consumers demand. This marriage of function and aesthetics will be crucial for consumer adoption.

The market potential is substantial, particularly in specialized applications where continuous operation is critical. Medical monitoring devices represent a particularly promising early-adoption sector, where the elimination of battery changes could significantly improve patient outcomes and reduce healthcare costs. As the broader wearable market expands toward $265 billion by 2030, body heat-powered solutions are poised to capture an increasing share.

Looking ahead, three key developments will accelerate progress:

1) Advancements in nano-engineered thermoelectric materials that push power densities beyond current limitations
2) Sophisticated AI algorithms for dynamic power management
3) Integration with emerging technologies like 6G connectivity

These innovations will gradually bridge the gapbetween concept and commercialization, potentially revolutionizing how we power wearable devices. The environmental implications are equally significant, offering a pathway to dramatically reduce e-waste from disposable batteries.

While technical challenges remain, the convergence of material science, energy harvesting technologies, and intelligent system design suggests that self-sustaining wearables may transition from niche applications to mainstream consumer products within this decade. This evolution promises not just incremental improvement, but a fundamental reimagining of wearable technology - one where devices draw energy continuously and unobtrusively from their users, eliminating charging routines while reducing environmental impact. The future of wearables may well be battery-free, and that future is closer than we think.

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